

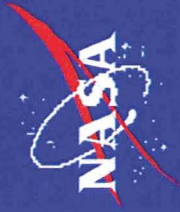
# Li-Ion Battery Studies at NASA/Goddard Space Flight Center

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# Content

- Background
- Test Program
- Test Batteries and Data
- Conclusions
- Acknowledgment

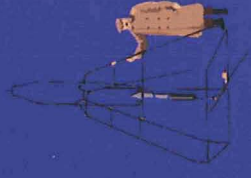






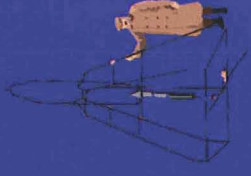
# Background

- Why Lithium-Ion (Li-Ion)?
  - High specific energy
  - High energy density
  - Benign handling requirements compared to nickel chemistry
- NASA/Goddard Space Flight Center's (GSFC's) interest in Li-Ion batteries
  - Maturity of chemistry for use in commercial applications
  - Infuse Li-Ion technology into NASA missions in particular Goddard Space Flight Center's Missions





# Background – contn'd

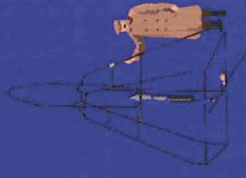


- GSFC Concerns?
  - Geo-Synchronous-Orbit (GEO) solstice storage
  - Low-Earth-Orbit (LEO) and Low-Lunar-Orbit (LLO) cycle life
  - Cell balancing
  - Overcharge
- GSFC Concern Mitigation
  - Cell/Battery procurement program began in 2002
    - ◇ Atomic Energy Authority Technology Battery Systems Ltd. (ABSL)
    - ◇ Japanese Storage Yuasa Technology Ltd. (JSYTL)
    - ◇ Quallion
    - ◇ SAFT
    - ◇ T/J Technologies Inc./A123 Systems
    - ◇ Yardney Technical Products (YTP), Lithion





# Test Program

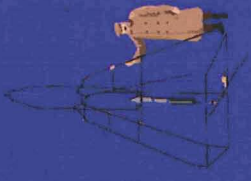


- Real-time GEO
  - Temperature:  $20 \pm 10^{\circ}\text{C}$
  - Eclipse Period: 42/23 days, Discharge at 0.6 C for a maximum shadow period of 72 minutes (approx. 70% Depth-of-discharge [DOD]), Charge at C/20 to a battery voltage clamp with taper for the remainder of daily solstice duration
  - Solstice Period: 140/160 days, battery voltage maintained at a battery voltage clamp (~70% State-of-charge [SOC])
  - Prior to each eclipse season, the battery is charged up to 100% SOC using C/20 charge rate to a battery voltage clamp with taper



## Test Program - contd.

- LEO
  - Temperature:  $20 \pm 2^{\circ}\text{C}$
  - DOD: approx. 30 to 40%
  - Discharge: Constant current for 30/36 minutes
  - Charge: Constant current to a battery voltage clamp with taper (55/60 minutes)



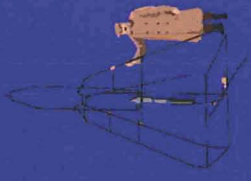




# Test Program - contd.

- LLO

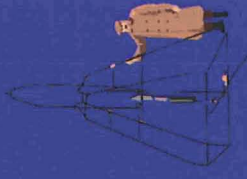
- Temperature:  $20 \pm 2^{\circ}\text{C}$
- DOD: 30 or 40% (minimum once a year 80%)
- Discharge: Constant current for 48 minutes (120/160 minutes for 80% DoD)
- Charge: Constant current to a battery voltage clamp with taper (65 minutes)





# Test Program - contd.

- Cell Voltage Divergence
  - For small cells in series and parallel configuration
  - Both GEO and LEO profiles were executed in sequence

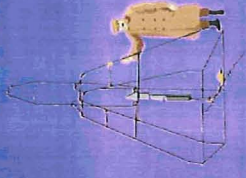






# Test Batteries and Data

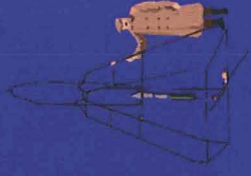
- Real-time GEO
- LEO
- LLO
- Cell Voltage Divergence





# Real-time GEO

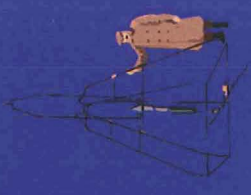
- ABSL
- JSYTL
- Saft
- YTP







## GEO: ABSL

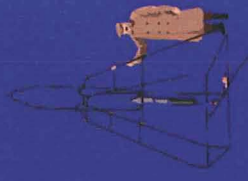


- **Battery Description**
  - 80 Ah Battery
  - 8s64p Sony 1.5Ah cells
  - Actual capacity at the test start: 83 Ah for a 40 A discharge to 24 V
- **Test Parameters**
  - 24-hour orbit
  - Eclipse Regime
    - Charge at 4 A to 33.6 V clamp with a taper to the end of the charge period
    - 42 days eclipse
    - Max. DOD 72%
    - Max. DOD days 21-23
    - Discharge current 48 A
  - Solstice Regime
    - 140 days
    - Voltage clamp at 32.3 V (72% SOC)
    - Capacity checked and fully charged prior to commencement of each eclipse season



## GEO: ABSL -contd.

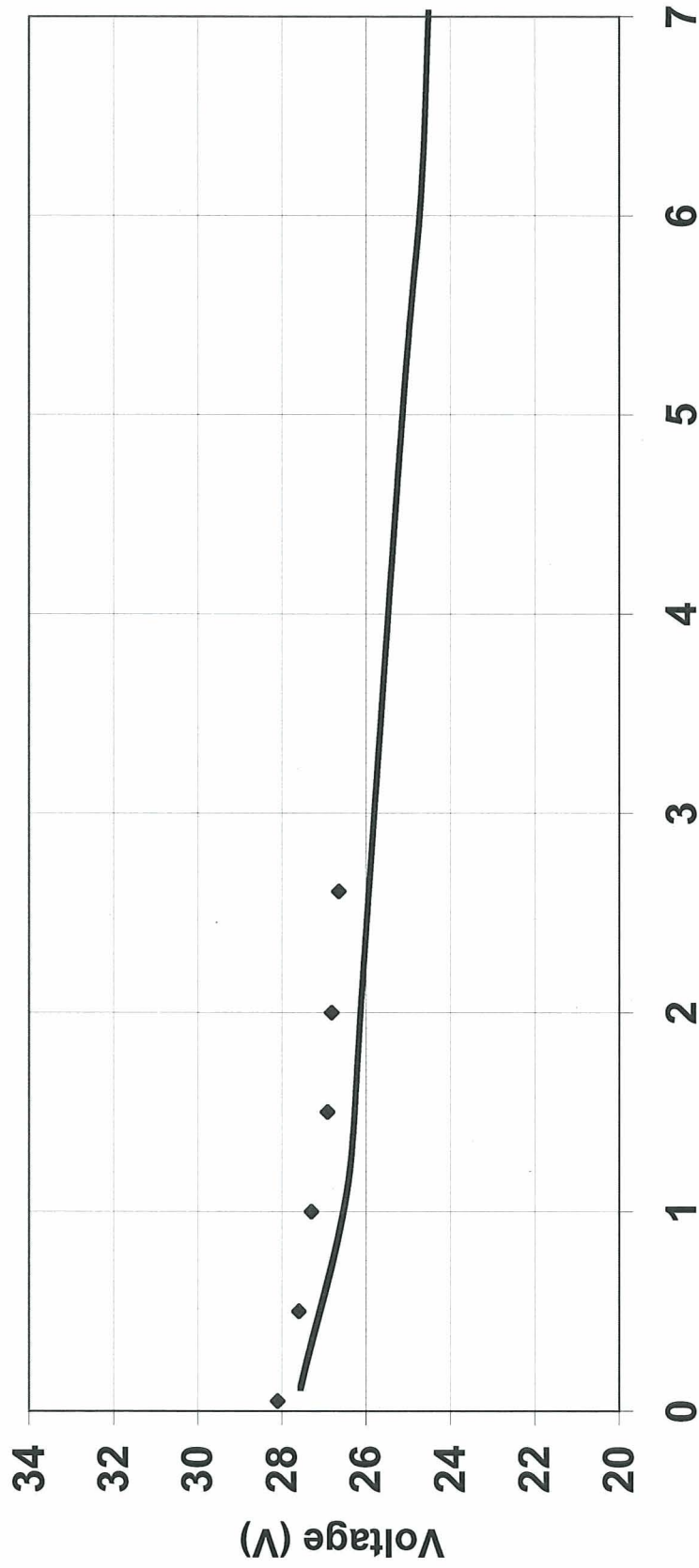
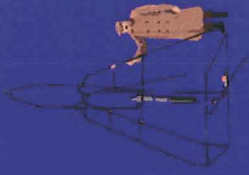
- Current Status
  - in eclipse season 7
  - Day 18, 68-minute eclipse period
  - End-of-discharge (EOD) 26.85 V
  - Actual capacity at the start of the 7th eclipse: 75 Ah
  - Min. battery voltage trend is shown in the following page







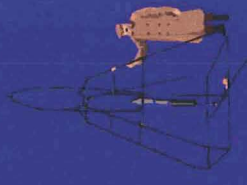
## GEO: ABSL -contd.



◆ Measured Minimum Voltage    — Calculated Minimum Voltage



# GEO: JSYTL I



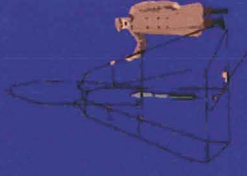
- **Battery Description**
  - 100 Ah Battery
  - 4s
  - Actual capacity at the test start: 113 Ah for a 50 A discharge to 24 V
- **Test Parameters**
  - 24-hour orbit
  - Eclipse Regime
    - Charge at 5 A to 16 V (at battery 32 V) clamp with a taper to end of the charge period
    - 42 days eclipse
    - Max. DOD 72%
    - Max. DOD days 21-23
    - Discharge current 60 A
  - Solstice Regime
    - 140 days
    - Voltage clamp at 15.5 V (at battery 31 V) [70% SOC]
    - Capacity checked and fully charged prior to commencement of each eclipse season





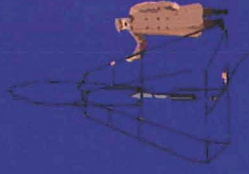
## GEO: JSYTL I-contd.

- Current Status
  - In solstice 7
  - EOD 14.47 V (at battery 28.54 V)
  - Actual capacity at the start of the 7th eclipse: 96 Ah
  - Max. cell voltage divergence 6 mV, no cell balancing circuitry
  - Min. battery voltage trend is shown in the following page

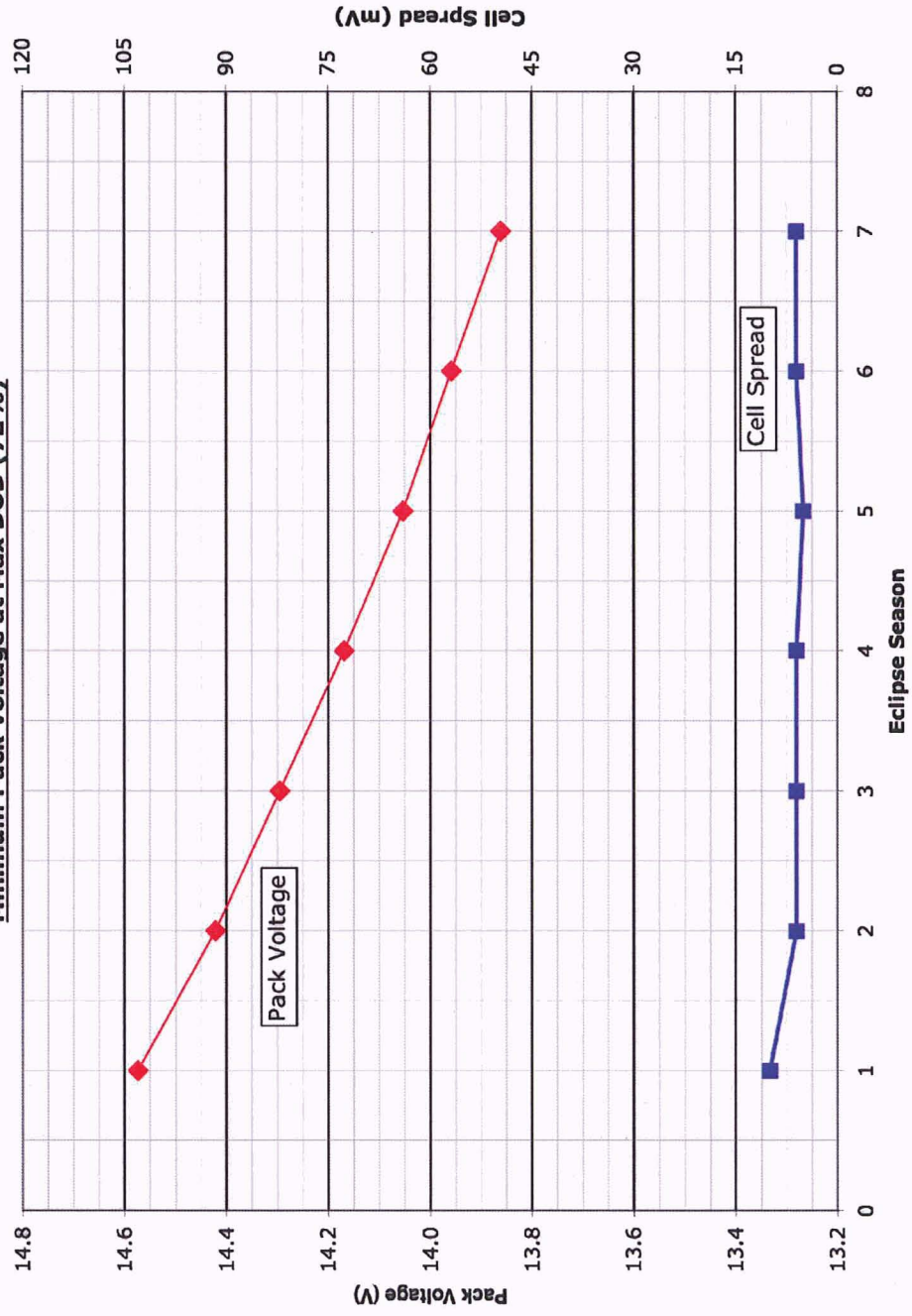




## GEO: JSYTL I-contd.



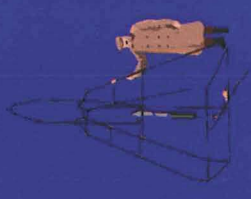
**JSB 100Ah GEO Test Pack (4-cell pack)  
Minimum Pack Voltage at Max DOD (72%)**







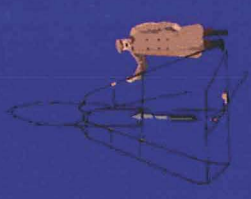
## GEO: JSYTL II



- **Battery Description**
  - 100 Ah Battery
  - 8s
  - Actual capacity at the test start: 111 Ah for a 50 A discharge to 24 V
- **Test Parameters**
  - 24-hour orbit
  - Eclipse Regime
    - Charge at 5 A to 32 V clamp with a taper to end of the charge period
    - 23 days eclipse
    - Max. DOD 72%
    - Max. DOD day 13
    - Discharge current 60 A
  - Solstice Regime
    - 160 days
    - Voltage clamp at 31 V (70% SOC)
    - Capacity checked and fully charged prior to commencement of each eclipse season



## GEO: JSYTL II-contd.

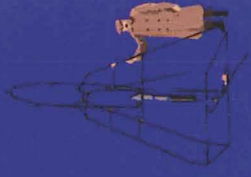


- Current Status
  - In solstice season 4
  - Actual capacity at the start of the 4th eclipse: 102 Ah
  - Max. cell voltage divergence 6 mV, no cell balancing circuitry
  - Min. battery voltage trend is shown in the following page

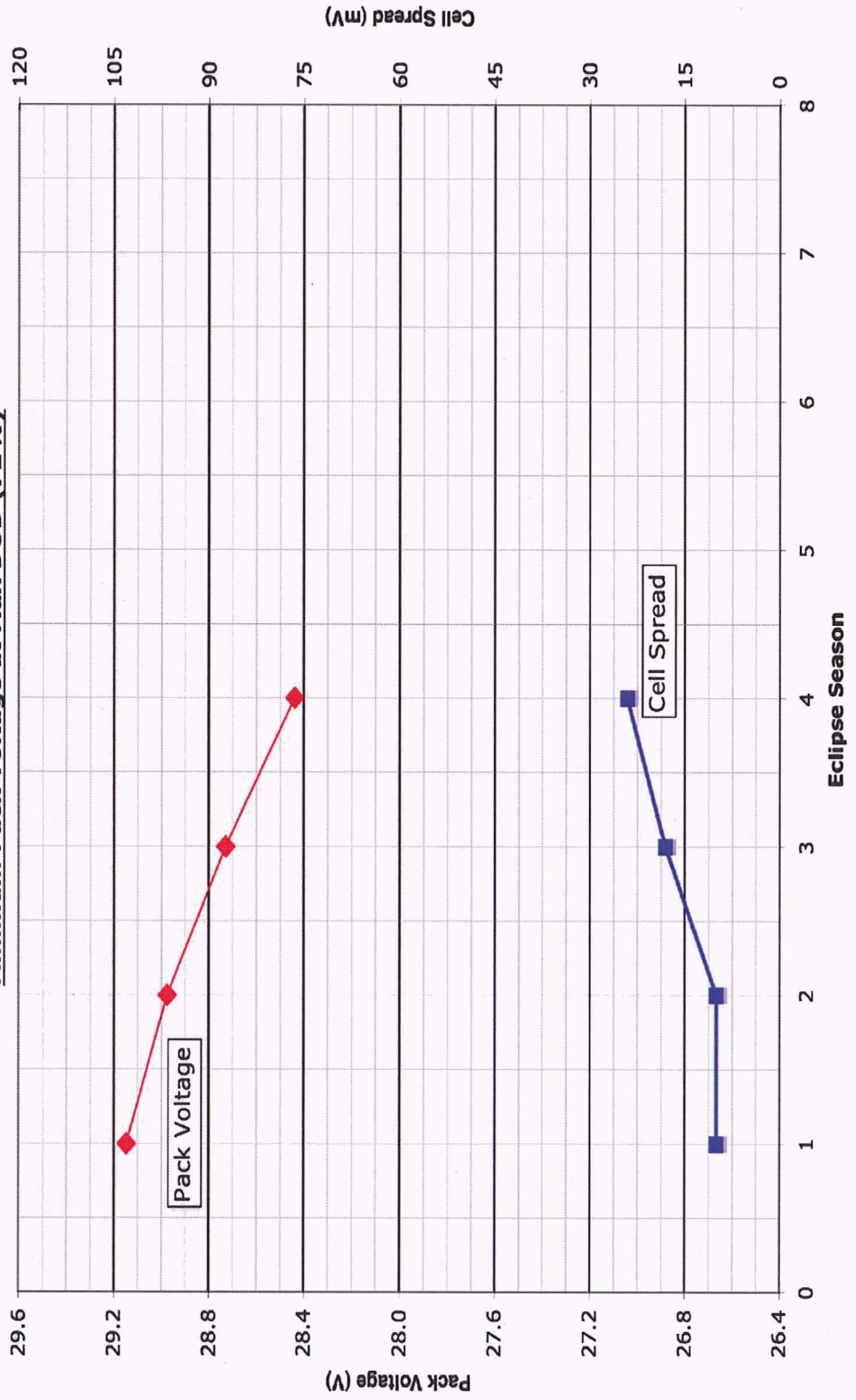




## GEO: JSYTL II-contd.



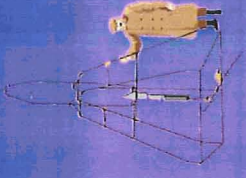
**JSB 100Ah GEO Test Pack (8-cell pack)**  
**Minimum Pack Voltage at Max DOD (72%)**







## GEO: Saft



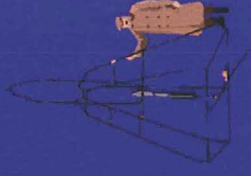
- **Battery Description**
  - 80 Ah Battery
  - 2p8s 40 Ah cells
  - Actual capacity at the test start: 98 Ah for a 40 A discharge to 24 V
- **Test Parameters**
  - 24-hour orbit
  - Eclipse Regime
    - Charge at 4 A to 32.8 V clamp with a taper to the end of the charge period
    - 42 days eclipse
    - Max. DOD 72%
    - Max. DOD days 21-23
    - Discharge current 48 A
  - Solstice Regime
    - 140 days
    - Voltage clamp at 30.8 V (70% SOC)
    - Fully charged prior to commencement of each eclipse season
    - Capacity checked only after the 3rd solstice when max. cell voltage divergence exceeded 80 mV, the cell balancing circuitry then turned on at the beginning of the 4th eclipse





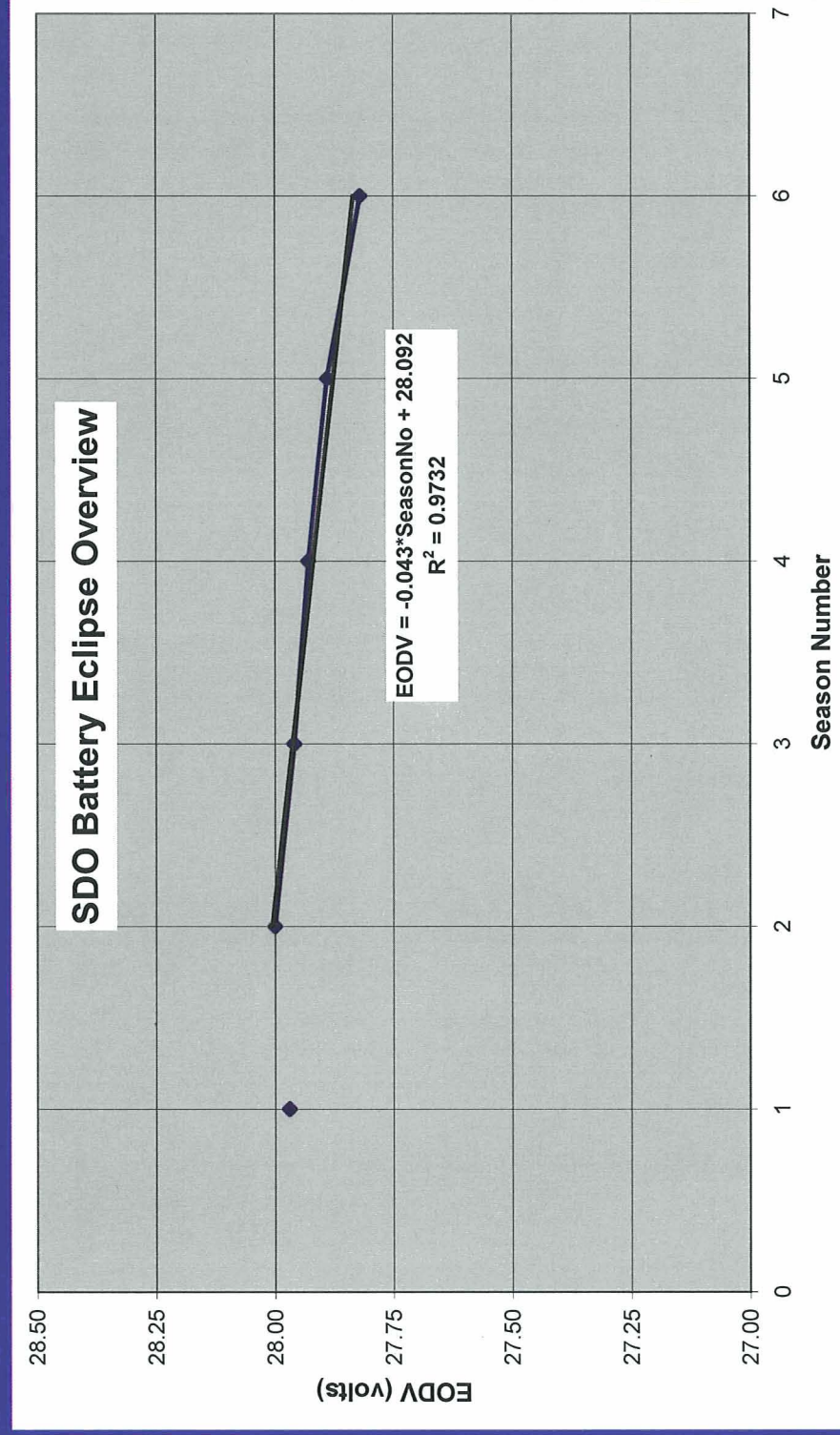
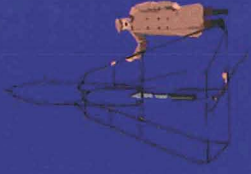
## GEO: Saft -contd.

- Current Status
  - in solstice season 6
  - Actual capacity at the start of the 6th eclipse: 94 Ah
  - Max. cell voltage divergence 13 mV (eclipse 6)
  - Min. battery voltage trend is shown in the following page





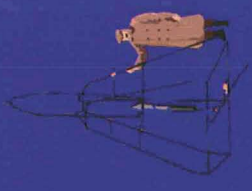
## GEO: Saft -contd.







## GEO: YTP

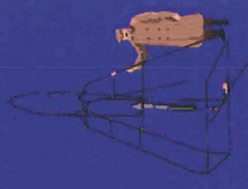


- **Battery Description**
  - 100 Ah Battery
  - 2s2p 50 Ah cells
  - Actual capacity at the test start: 118 Ah for a 50 A discharge to 24 V
- **Test Parameters**
  - 24-hour orbit
  - Eclipse Regime
    - Charge at 5 A to 8.2 V (at battery 32.8 V) clamp with a taper to end of the charge period
    - 42 days eclipse
    - Max. DOD 72%
    - Max. DOD days 21-23
    - Discharge current 60 A
  - Solstice Regime
    - 160 days
    - Voltage clamp at 7.7 V (at battery 30.8 V) [70% SOC]
    - Capacity checked and fully charged prior to commencement of each eclipse season



## GEO: YTP-contd.

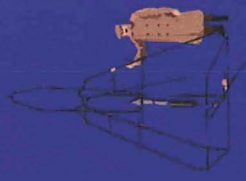
- Current Status
  - In solstice season 6
  - Actual capacity at the start of the 6th eclipse: 113 Ah
  - Max. cell voltage divergence 90 mV (eclipse 6), no cell balancing circuitry
  - Minimum battery voltage trend is shown in the following page



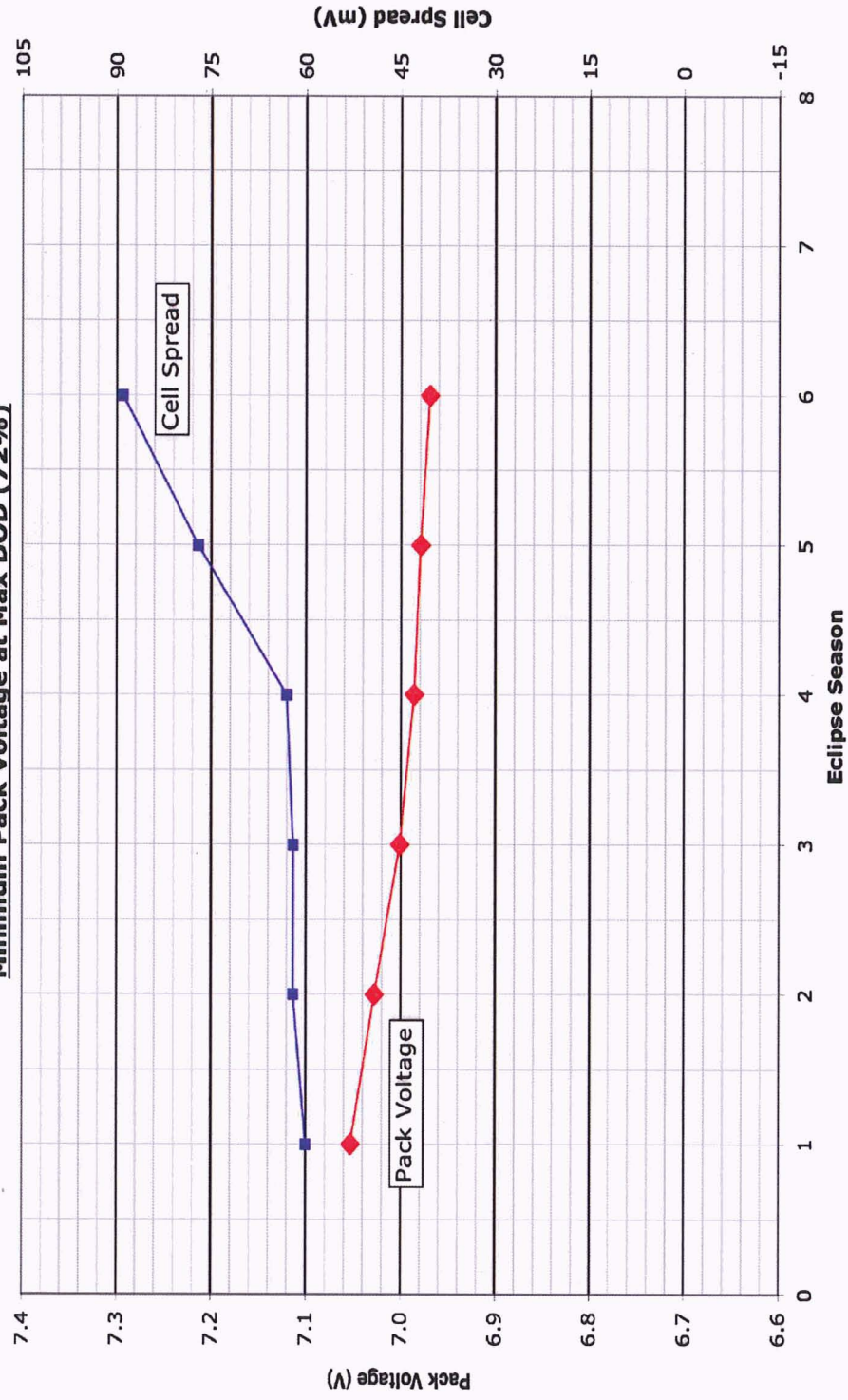




# GEO: YTP-contd.



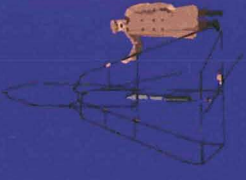
**YTP 50Ah GEO Test Pack (wired as 2P-2S 100Ah pack)  
Minimum Pack Voltage at Max DOD (72%)**





# LEO

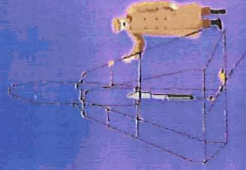
- JSYTL
- Quallion
- Saft
- T/J Tech.
- YTP







# LEO: JSYTL I

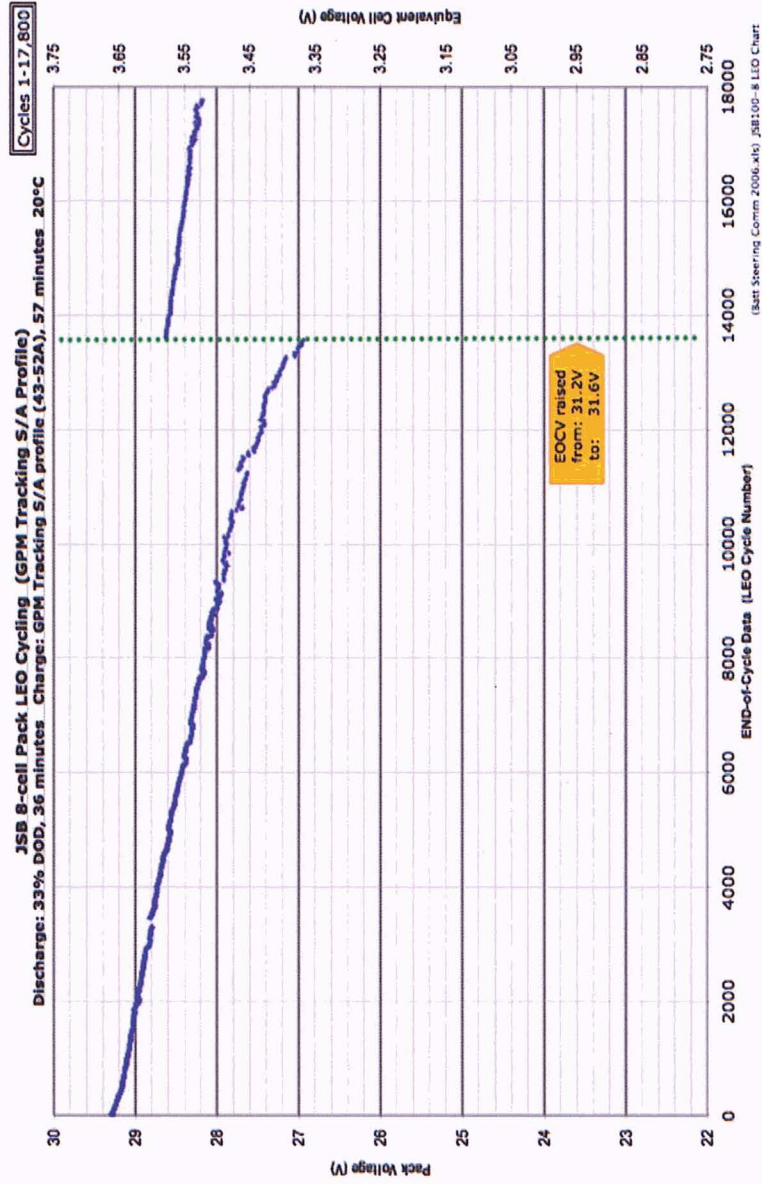


- **Battery Description**
  - 100 Ah Battery
  - 8s
  - Actual capacity at the test start: 113 Ah for a 50 A discharge to 24 V
- **Test Parameters**
  - 93-minute orbit
  - Charge at 43-52 A to 31.2 V for 13500 cycles and then 31.6 V clamp with a taper to end of the charge period of 57 minutes
  - Discharge current 55 A for 36 minutes
  - DOD 33%
- **Current Status**
  - Completed 18770 cycles
  - EOD 28.15 V
  - EOD voltage trend is shown in the following page
  - Max. cell voltage divergence 90 mV around 13500 cycles, 50 mV after changing the charge voltage from 31.2 to 31.6 V, no cell balancing circuitry
  - One capacity check was performed after the 1820th cycle: 104 Ah





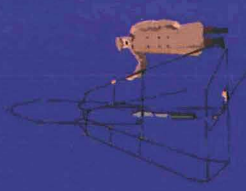
# LEO: JSYTL I-contd.







## LEO: JSYTL II



- **Battery Description**

- 175 Ah Battery
- 8s
- Actual capacity at the test start: 183 Ah for a 87.5 A discharge to 24 V

- **Test Parameters**

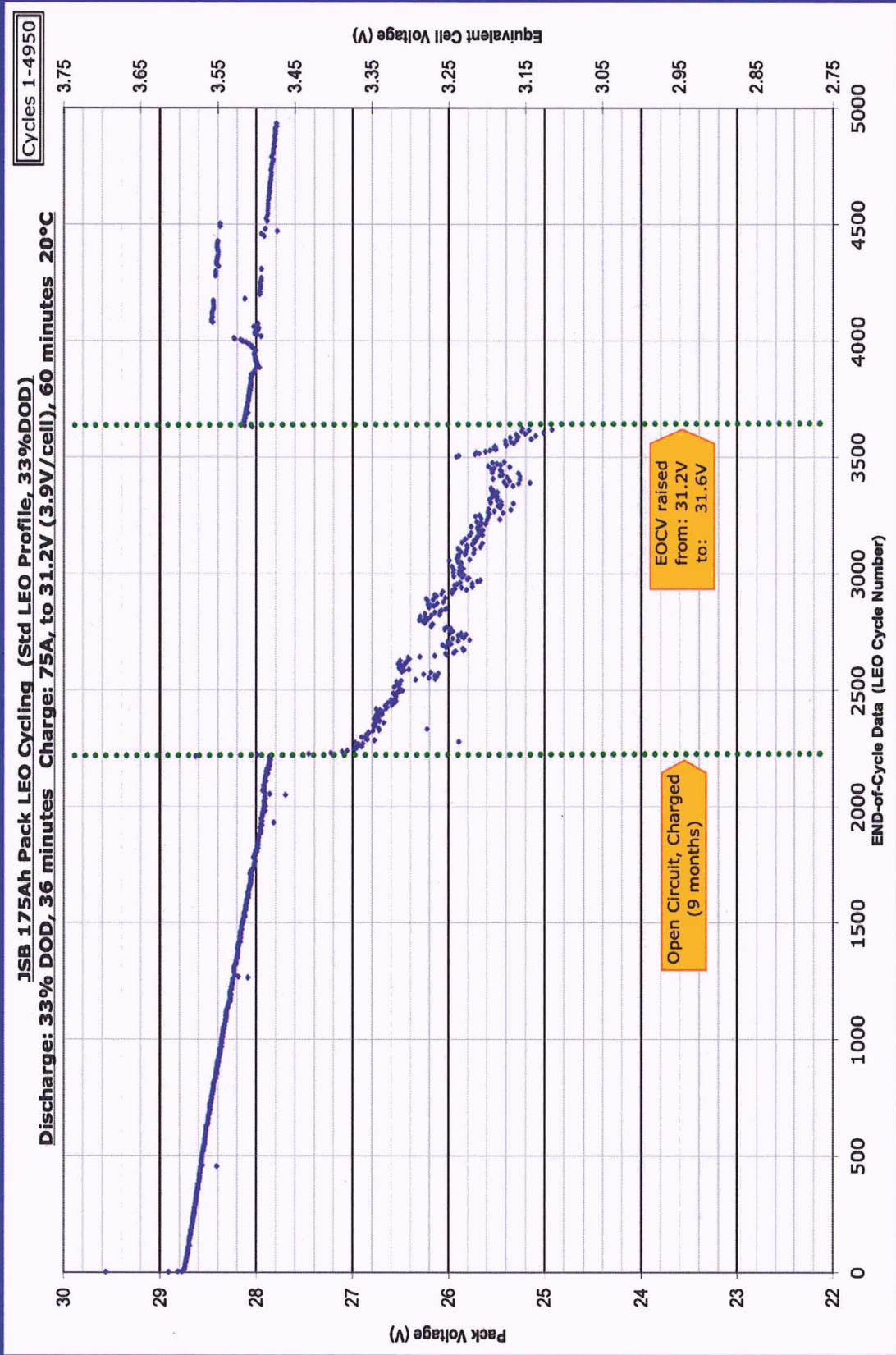
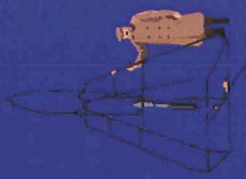
- 93-minute orbit\*
- Charge at 75 A to 31.2 V for 3600 cycles and then 31.6 V clamp with a taper to end of the charge period of 57 minute
- Discharge current 96 A for 36 minutes
- DOD 33%
- \* 25% DOD, 60 A charge rate and 73 A discharge rate for the first 600 cycles

- **Current Status**

- Completed 5138 cycles
- EOD 27.91 V
- EOD voltage trend is shown in the following page
- Max. cell voltage divergence 320 mV around 3600 cycles, 44 mV after changing the charge voltage from 31.2 to 31.6 V, no cell balancing circuitry
- One capacity check was performed after the 600th cycle: 104 Ah
- Open-circuit stand for 9 months due to system problem



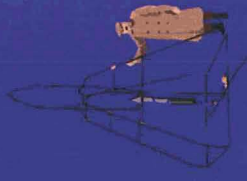
# LEO: JSYTL II-contd.







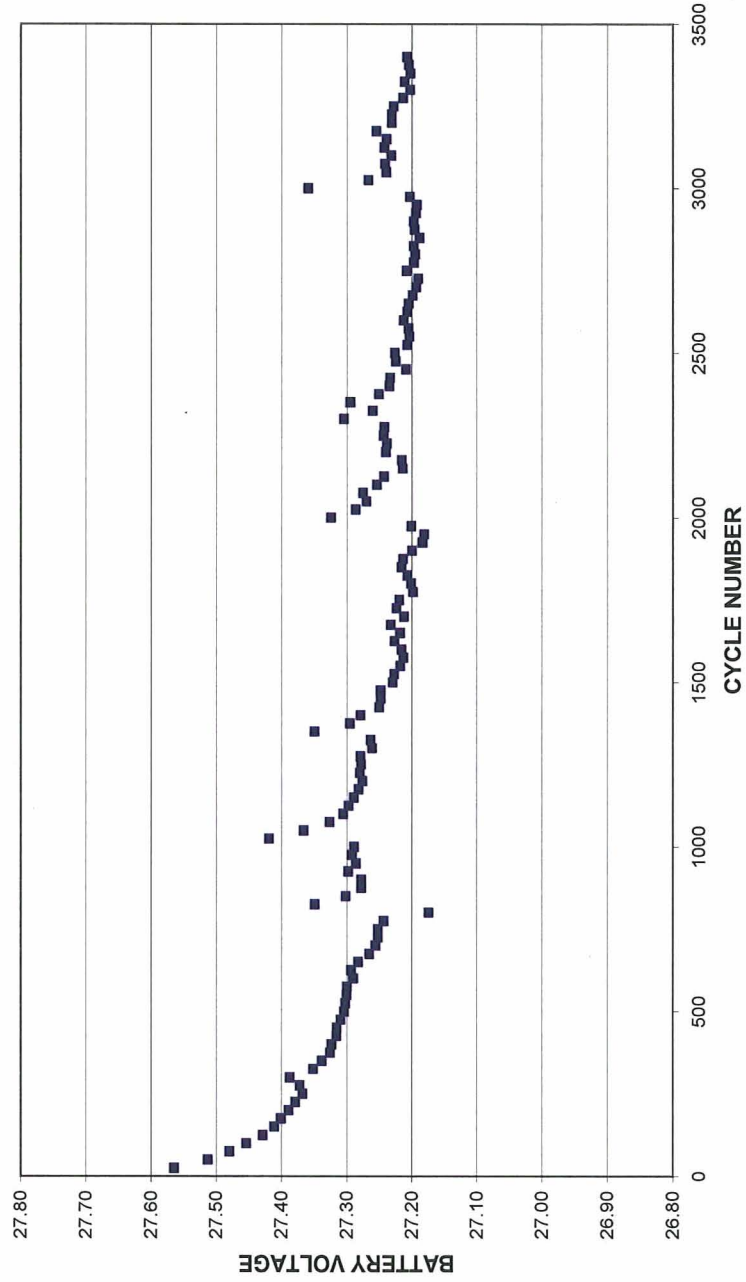
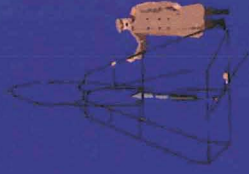
## LEO: Quallion I



- **Battery Description**
  - 3 Ah Battery
  - 3p8s Sony 1.5Ah cells
  - Actual capacity at the test start: 3.7 Ah for a 1.5 A discharge to 24 V
- **Test Parameters**
  - 90-minute orbit
  - Charge at 1.5 A to 32 V clamp with a taper to end of the charge period of 60 minutes
  - Discharge current 2.4 A for 30 minutes
  - DOD 40%
- **Current Status**
  - Completed 3400 cycles
  - EOD 27.21 V
  - EOD voltage trend is shown in the following page



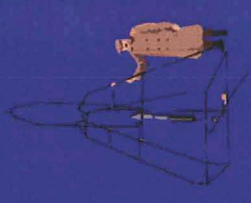
## LEO: Quallion I-contd.







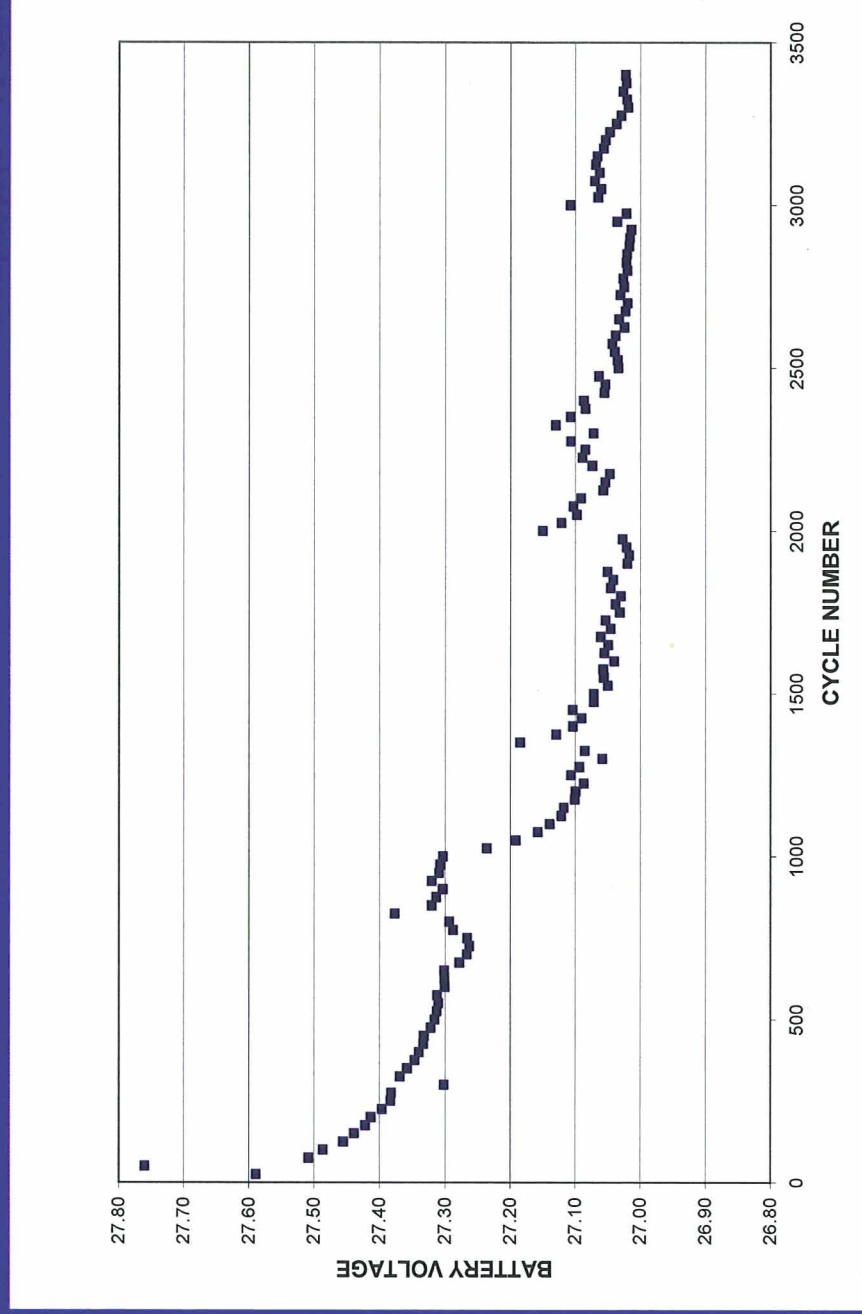
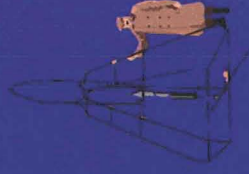
## LEO: Quallion II



- **Battery Description**
  - 6 Ah Battery
  - 6p8s Sony 1.5Ah cells
  - Actual capacity at the test start: 7.4 Ah for a 3 A discharge to 24 V
- **Test Parameters**
  - 90-minute orbit
  - Charge at 3 A to 32 V clamp with a taper to end of the charge period of 60 minutes
  - Discharge current 4.8 A for 30 minutes
  - DOD 40%
  - Removed one cell at 1000th cycle; to understand the performance of the battery with a failed cell
- **Current Status**
  - Completed 3400 cycles
  - EOD 27.02 V
  - EOD voltage trend is shown in the following page



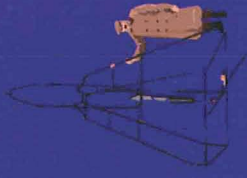
# LEO: Quallion II-contd.







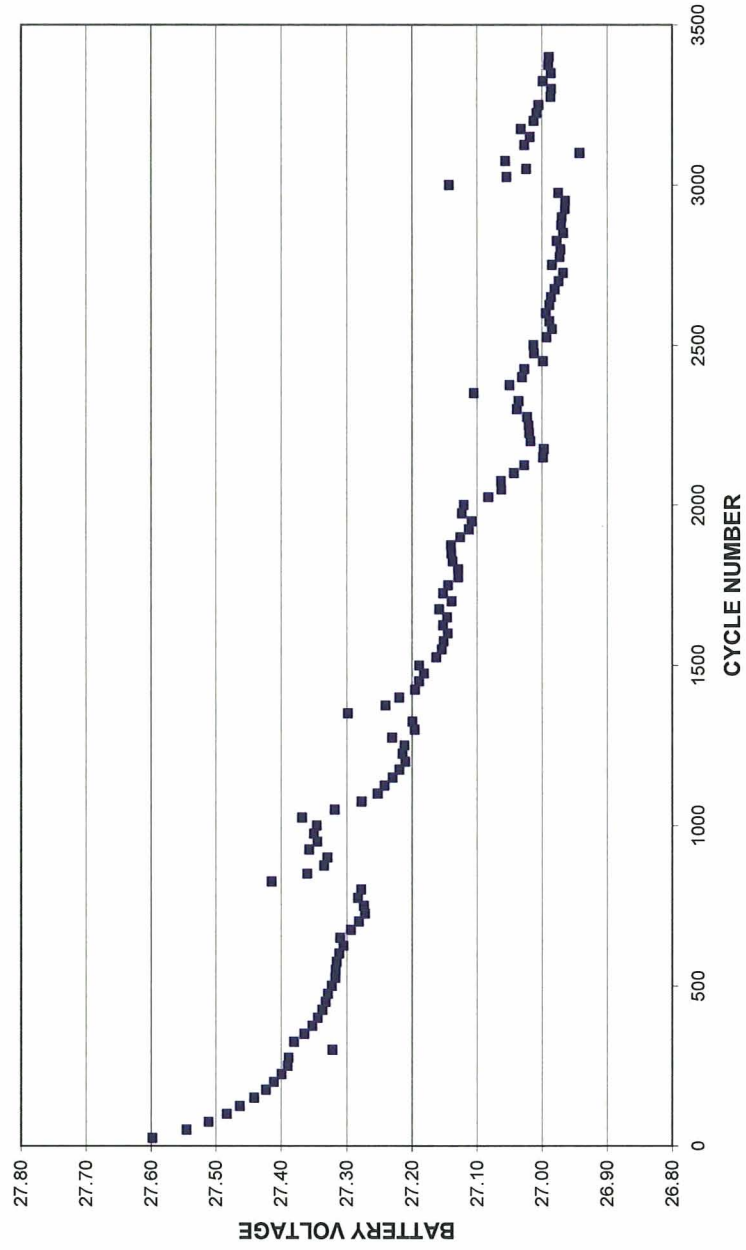
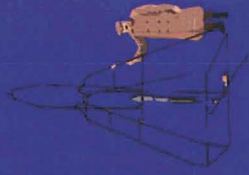
## LEO: Quallion III



- **Battery Description**
  - 9 Ah Battery
  - 9p8s Sony 1.5Ah cells
  - Actual capacity at the test start: 11.1 Ah for a 4.5 A discharge to 24 V
- **Test Parameters**
  - 90-minute orbit
  - Charge at 4.5 A to 32 V clamp with a taper to end of the charge period of 60 minutes
  - Discharge current 7.2 A for 30 minutes
  - DOD 40%
  - Removed one cell at 1000th cycle and another at 2000th cycle; to understand the performance of the battery with two failed cells
- **Current Status**
  - Completed 3400 cycles
  - EOD 26.99 V
  - EOD voltage trend is shown in the following page



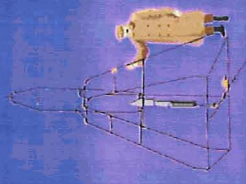
## LEO: Quallion III-contd.







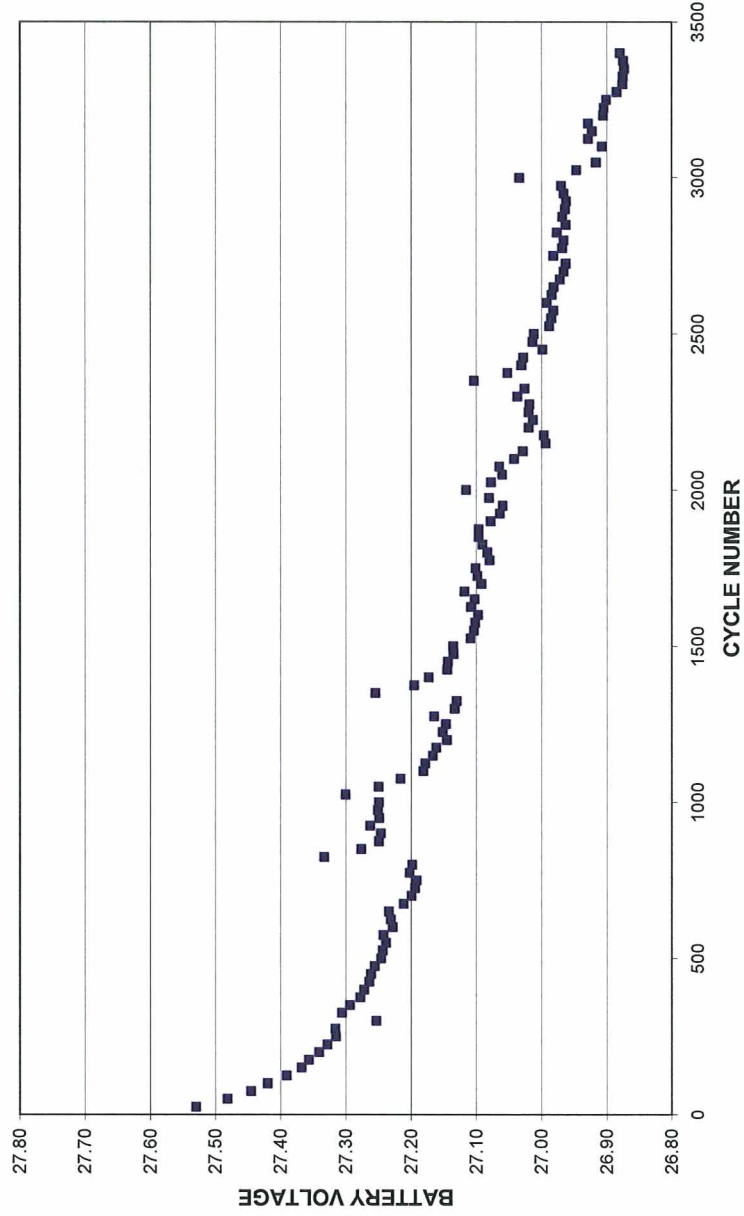
## LEO: Quallion IV



- **Battery Description**
  - 12 Ah Battery
  - 12p8s Sony 1.5Ah cells
  - Actual capacity at the test start: 14.7 Ah for a 6 A discharge to 24 V
- **Test Parameters**
  - 90-minute orbit
  - Charge at 6 A to 32 V clamp with a taper to end of the charge period of 60 minutes
  - Discharge current 9.6 A for 30 minutes
  - DOD 40%
  - Removed one cell at 1000th cycle, second at 2000th cycle and the third at 3000th cycle; to understand the performance of the battery with three failed cells
- **Current Status**
  - Completed 3400 cycles
  - EOD 26.88 V
  - EOD voltage trend is shown in the following page



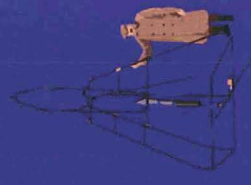
## LEO: Quallion IV-contd.







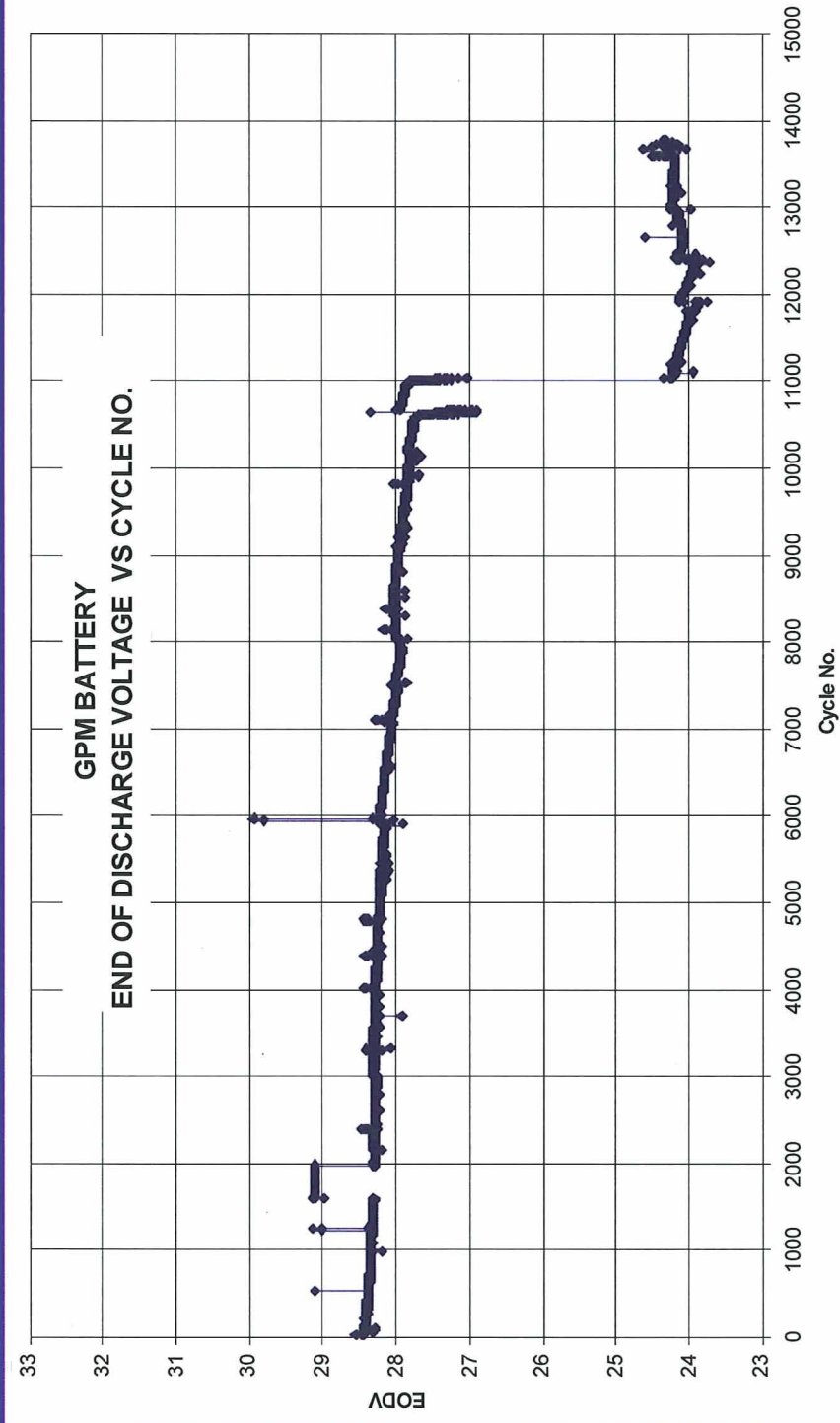
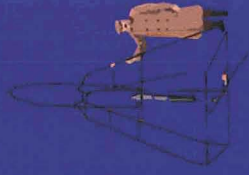
## LEO: Saft



- **Battery Description**
  - 80 Ah Battery
  - 2p8s 40Ah cells but 2p7s after 11000 cycles
  - Actual capacity at the test start: 98 Ah for a 40 A discharge to 24 V
- **Test Parameters**
  - 92-minute orbit
  - Charge at 44 A to 31.2 V up to 11000 cycles and then to 28 V clamp with a taper to end of the charge period of 56 minutes
  - Discharge current 44 A up to 11000 cycles and then 50 A for 36 minutes
  - DOD 33% up to 11000 cycles and then 38%
  - Cell balancing circuitry active
- **Current Status**
  - Test Anomaly: A cell pair developed an internal short at 11000th cycle, the battery was converted into a 2p7s configuration
  - Completed 14410 cycles
  - EOD 24.23 V
  - EOD voltage trend is shown in the following page
  - Max. cell voltage divergence 111 mV during discharge



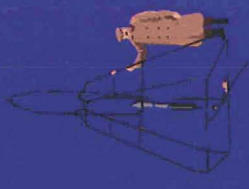
## LEO: Saft-contd.







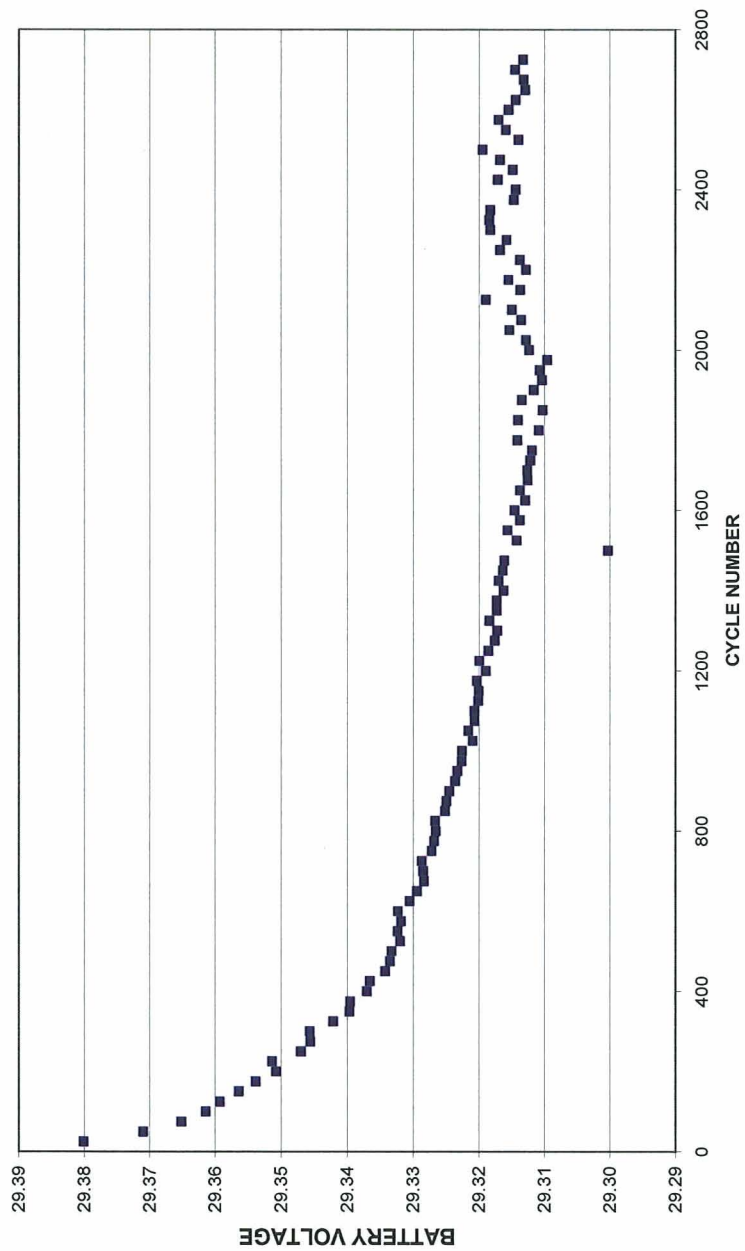
## LEO: T/J Tech.



- **Battery Description**
  - 10 Ah Battery
  - 5p9s A123 2.2 Ah cells
  - Actual capacity at the test start: 11.5 Ah for a 5 A discharge to 24 V
- **Test Parameters**
  - 90-minute orbit
  - Charge at 4.4 A to 32.4 V clamp with a taper to end of the charge period of 60 minutes
  - Discharge current 8 A for 30 minutes
  - DOD 40%
- **Current Status**
  - Completed 2725 cycles
  - EOD 29.31 V
  - EOD voltage trend is shown in the following page



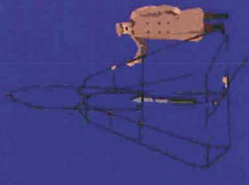
# LEO: T/J Tech.-contd.







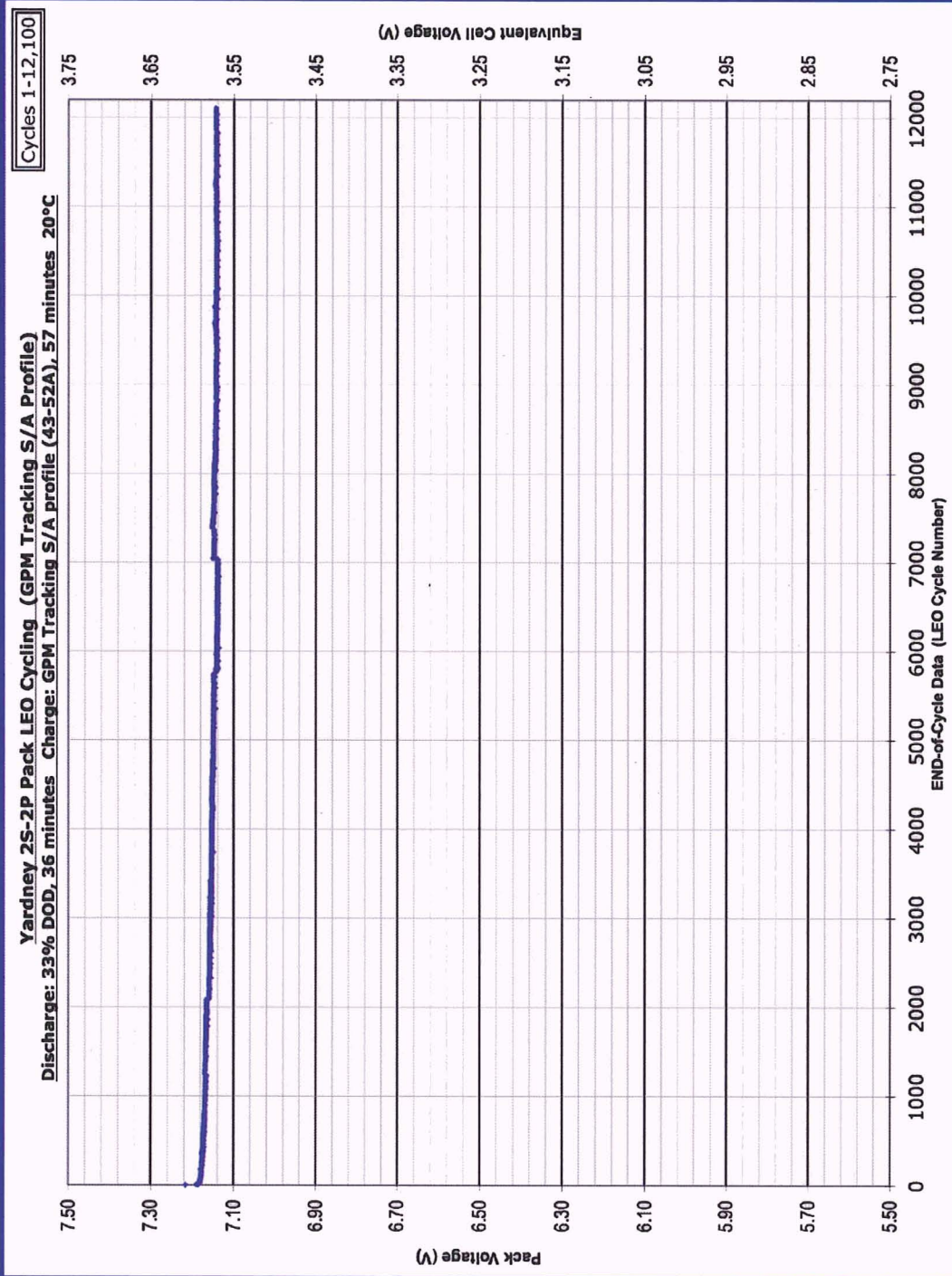
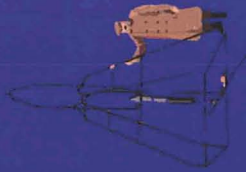
## LEO: YTP I



- **Battery Description**
  - 100 Ah Battery
  - 2p2s 50 Ah cells
  - Actual capacity at the test start: 117 Ah for a 50 A discharge to 6 V (at battery 24 V)
- **Test Parameters**
  - 93-minute orbit
  - Charge at 43-52 A to 7.8 V (at battery 31.2 V) up to 12400 cycles and then 7.9 V (31.6 V) clamp with a taper to end of the charge period of 57 minutes
  - Discharge current 55 A for 36 minutes
  - DOD 33%
- **Current Status**
  - Completed 13440 cycles
  - EOD 7.23 V (at battery 28.92 V)
  - Max. cell voltage divergence 134 mV but decreased to 81 mV after charge voltage change from 7.8 to 7.9 V, no cell balancing circuitry
  - EOD voltage trend is shown in the following page



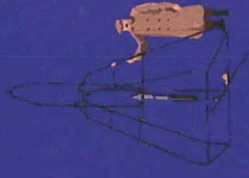
# LEO: YTP I-contd.







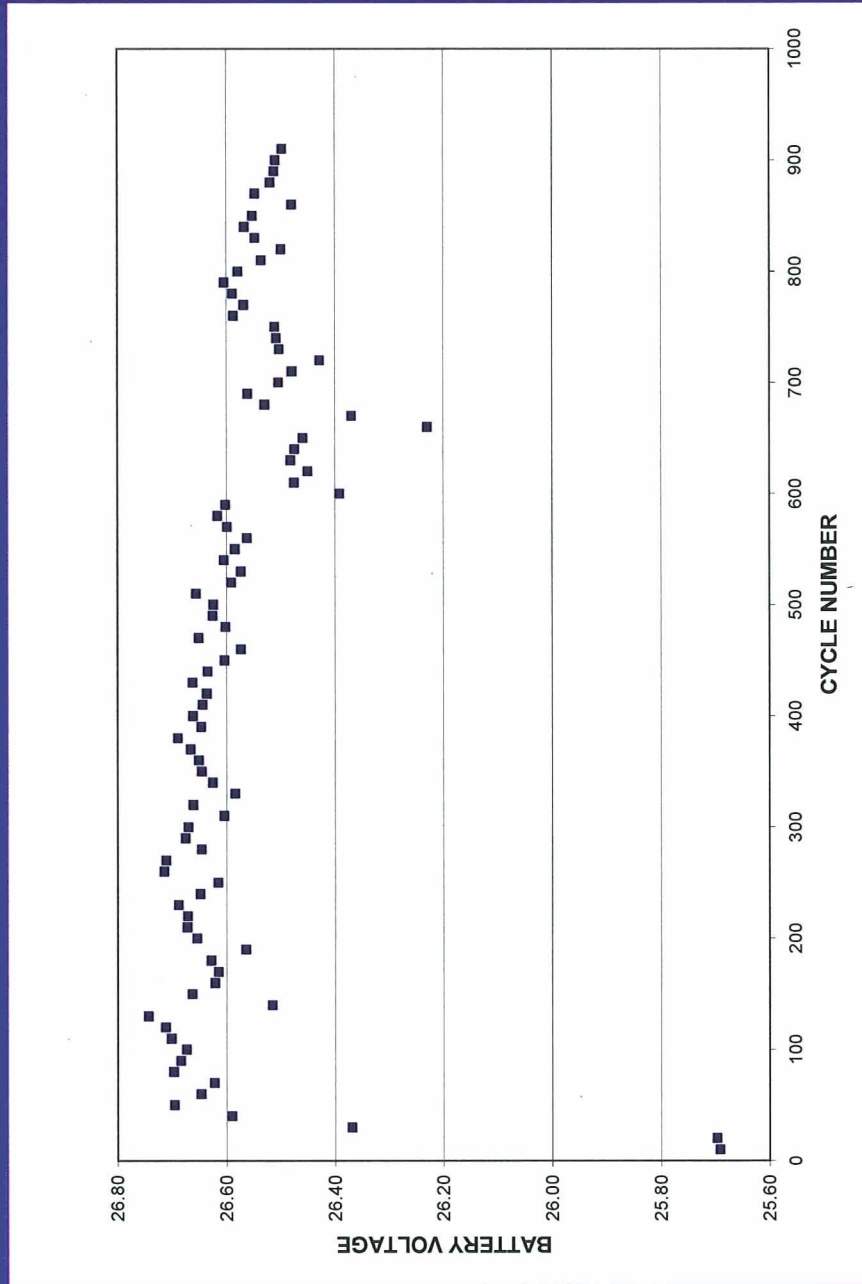
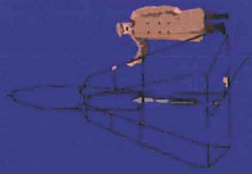
## LEO: YTP II



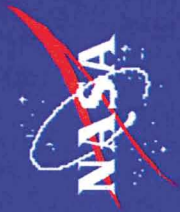
- **Battery Description**
  - 200 Ah Battery
  - 8s
  - Actual capacity at the test start: 203.8 Ah for a 100 A discharge to 24 V
- **Test Parameters**
  - 90-minute orbit
  - Charge at 96 A to 31.2 V clamp with a taper to end of the charge period of 55 minutes
  - Discharge current 137 A for 35 minutes
  - DOD 40%
- **Current Status**
  - Completed 910 cycles
  - EOD 26.5 V
  - Thermal problem from the beginning of the testing, test chamber is now controlled at 5°C but the battery temperature is about 23°C
  - Max. cell voltage divergence 17 mV, cell balancing circuitry in active
  - EOD voltage trend is shown in the following page



# LEO: YTP II-contd.







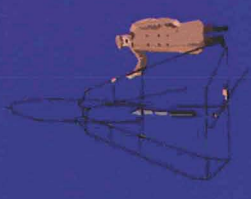
# LLO

- ABSL
- JSYTL
- Quallion
- Saft
- YTP





## LLO: ABSL



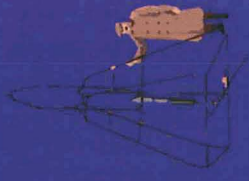
- **Battery Description**
  - 60 Ah Battery
  - 8s48p Sony 1.5Ah cells
  - Actual capacity at the test start: 62 Ah for a 30 A discharge to 24 V
- **Test Parameters**
  - 32% DOD
  - 113-minute orbit
  - Charge at 27 A to 33.6 V clamp with a taper to end of the charge period of 65 minutes
  - Discharge current 24 A for 48 minutes
  - 80% DOD
  - Once in every six months 225-minute orbit
  - Charge at 27 A to 33.6 V clamp with a taper to end of the charge period of 65 minutes
  - Discharge current 18 A for 160 minutes





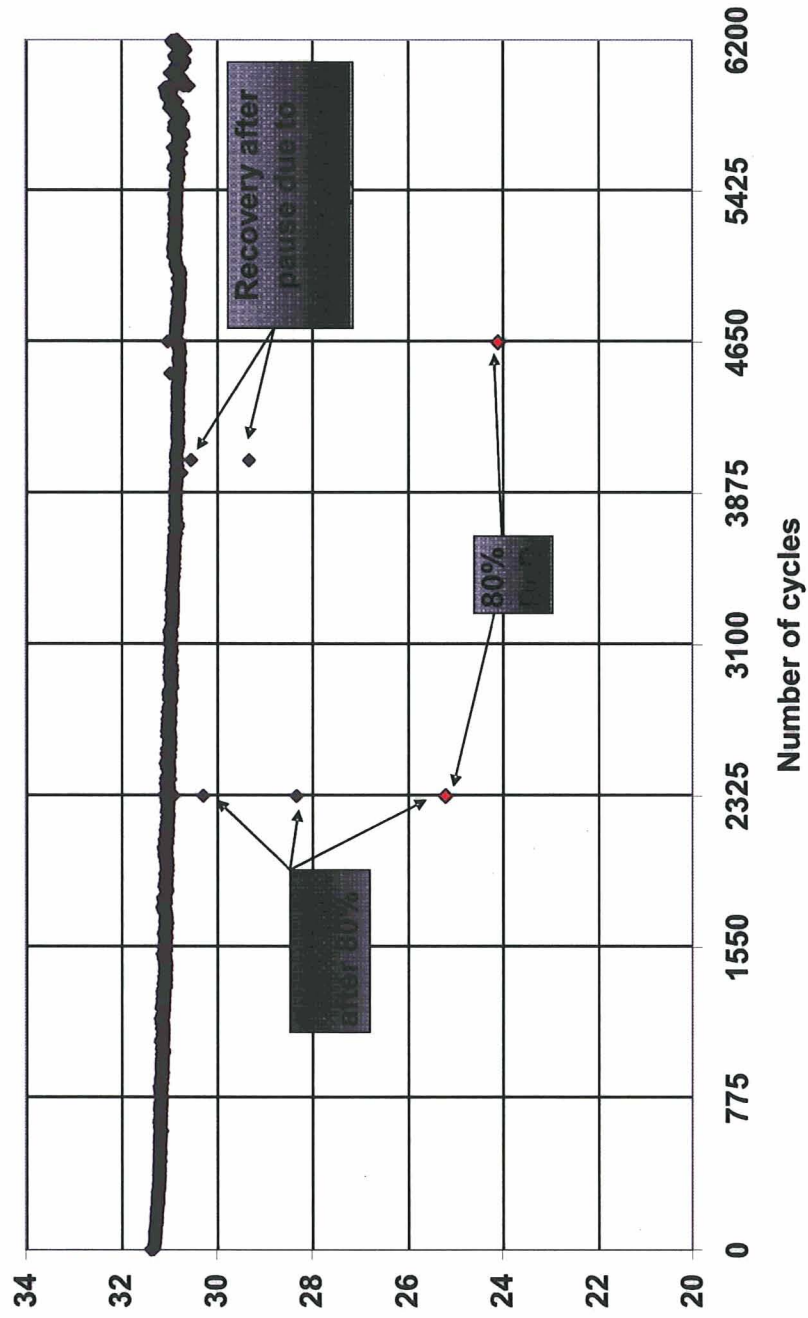
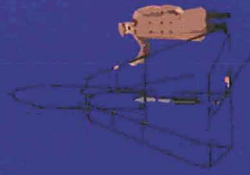
## LLO: ABSL-contd.

- Current Status
  - Completed 7200 cycles, of which 3 were 80% DOD
  - EOD 28.15 V for 32% DOD
  - EOD 23.6 V for the last 80% DOD
  - EOD voltage trend is shown in the following page
  - One capacity check was performed after the 6975th cycle: 50Ah





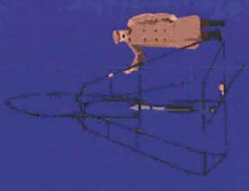
## LLO: ABSL-contd.







## LLO: JSYYL



- **Battery Description**
  - 50 Ah Battery
  - 8s
  - Actual capacity at the test start: 55 Ah for a 25 A discharge to 24 V
- **Test Parameters**
  - 40% DOD
  - 113-minute orbit
  - Charge at 22 A to 31.2 V up to 2500 cycles and then 31.6 V clamp with a taper to end of the charge period of 65 minutes
  - Discharge current 25 A for 48 minutes
  - 80% DOD
  - Once in every six months 225-minute orbit
  - Charge at 22 A to 32 V for 1st and 32.4 V for 2nd, respectively, clamp with a taper to end of the charge period of 65 minutes
  - Discharge current 15 A for 160 minutes



## LLO: JSYTL-contd.

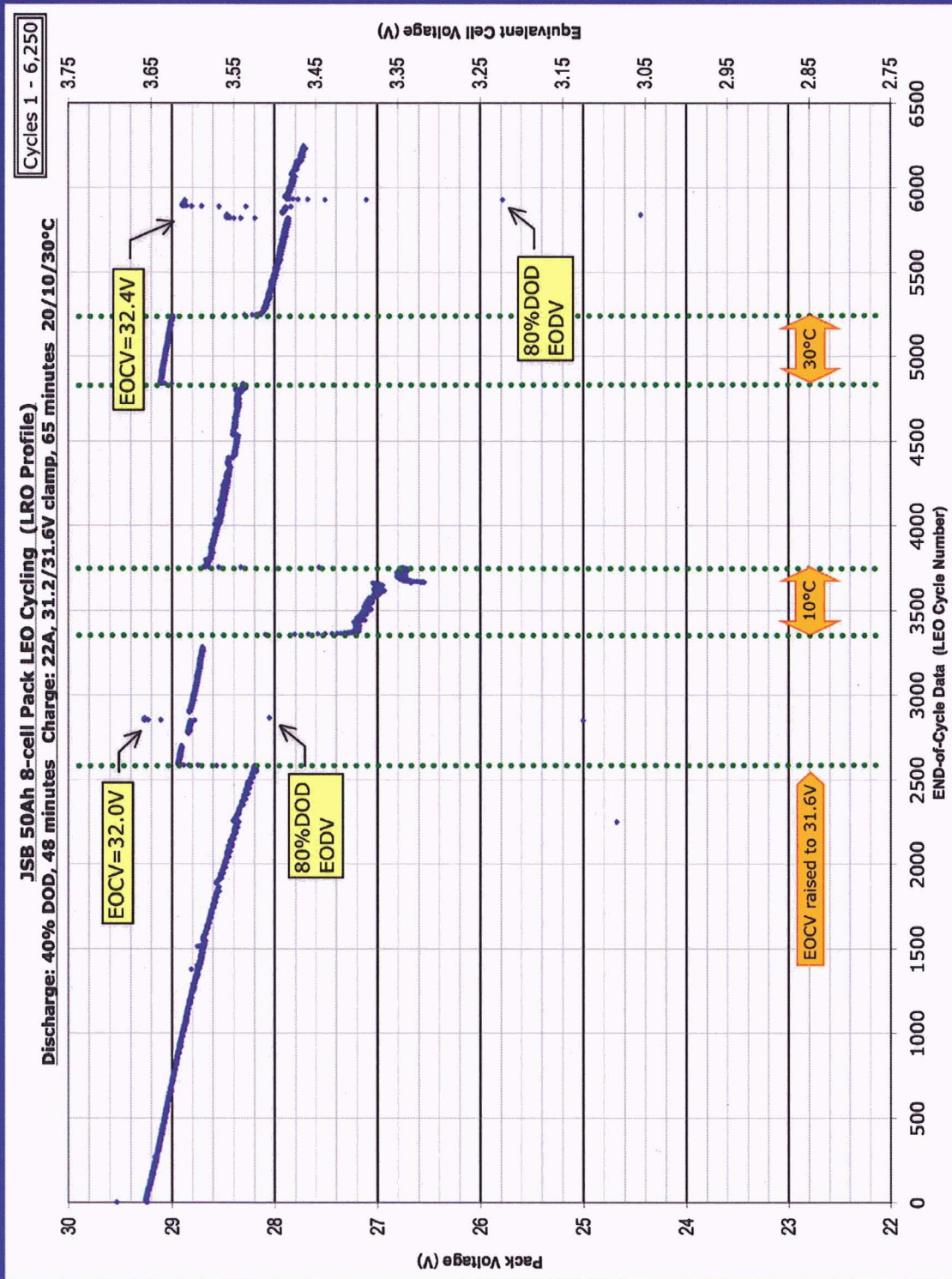
- Current Status
  - Completed 6850 cycles, of which 2 were 80% DOD
  - EOD 27.49 V for 32% DOD
  - EOD 25.8 V for the last 80% DOD
  - Max. cell voltage divergence 64 mV around 3000th cycle, changing charge clamp voltage from 31.2 to 31.6 V reduced the value to 39 mV, low temperature excursion to 10 and 30°C increased the value to 100 mV, no cell balancing circuitry
  - EOD voltage trend is shown in the following page, note 10°C and 30°C testing for 30 days, respectively





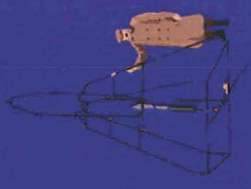


# LLO: JSYTL-contd.





# LLO: Quallion



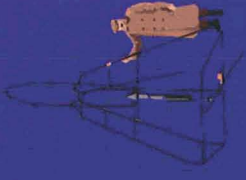
- **Battery Description**
  - 15 Ah Battery
  - 8s
  - Actual capacity at the test start: 14.1 Ah for a 7.5 A discharge to 24 V
- **Test Parameters**
  - 32% DOD
    - 113-minute orbit
    - Charge at 7 A to 31.6 V clamp with a taper to end of the charge period of 65 minutes
    - Discharge current 6 A for 48 minutes
  - 80% DOD
    - Once in every month 185-minute orbit
    - Charge at 7 A to 32.8 V clamp with a taper to end of the charge period of 65 minutes
    - Discharge current 6 A for 120 minutes





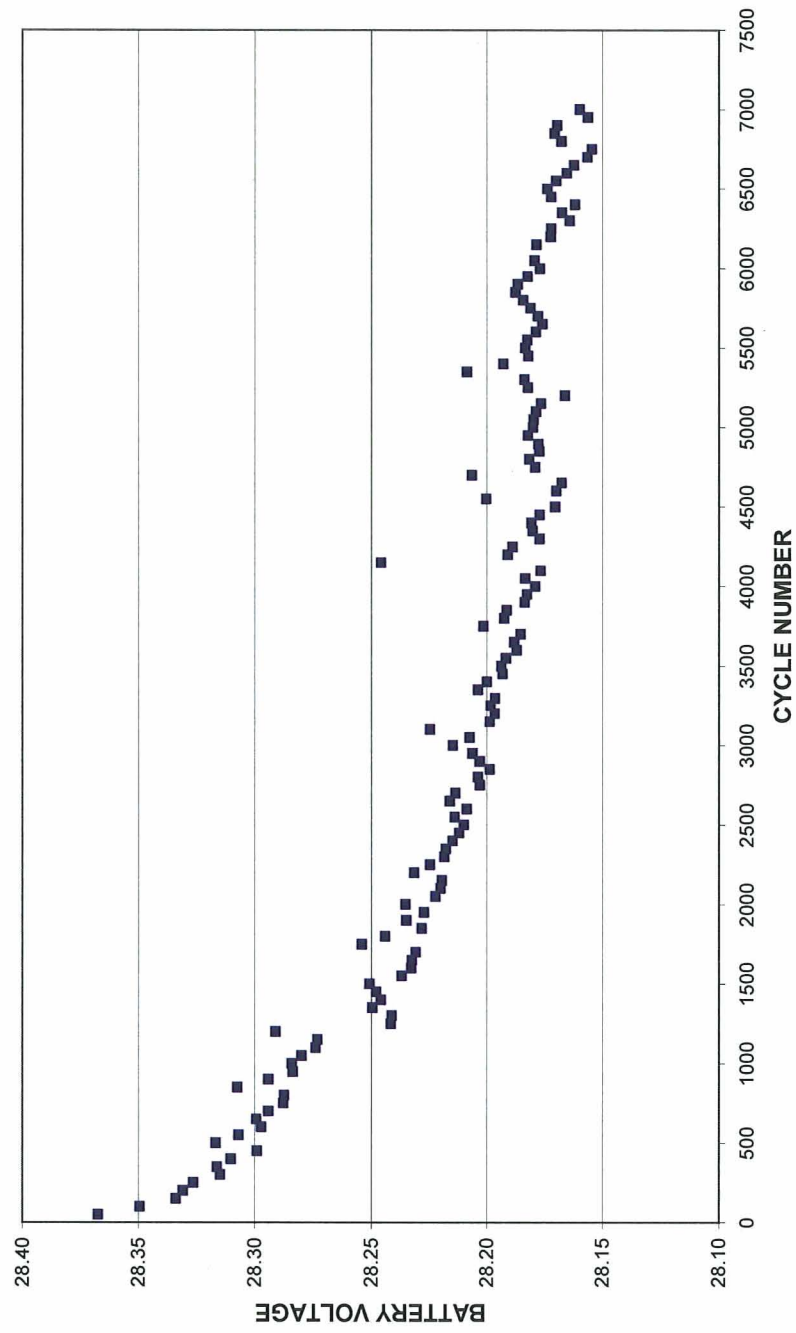
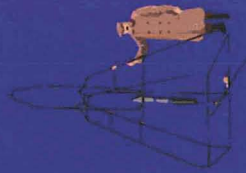
## LLO: Quallion-contd.

- Current Status
  - Completed 7000 cycles, of which 17 were 80% DOD
  - EOD 28.16 V for 32% DOD
  - EOD 26.02 V for the last 80% DOD
  - Max. cell voltage divergence 145 mV, no cell balancing circuitry
  - EOD voltage trend is shown in the following page





## LLO: Quallion-contd.

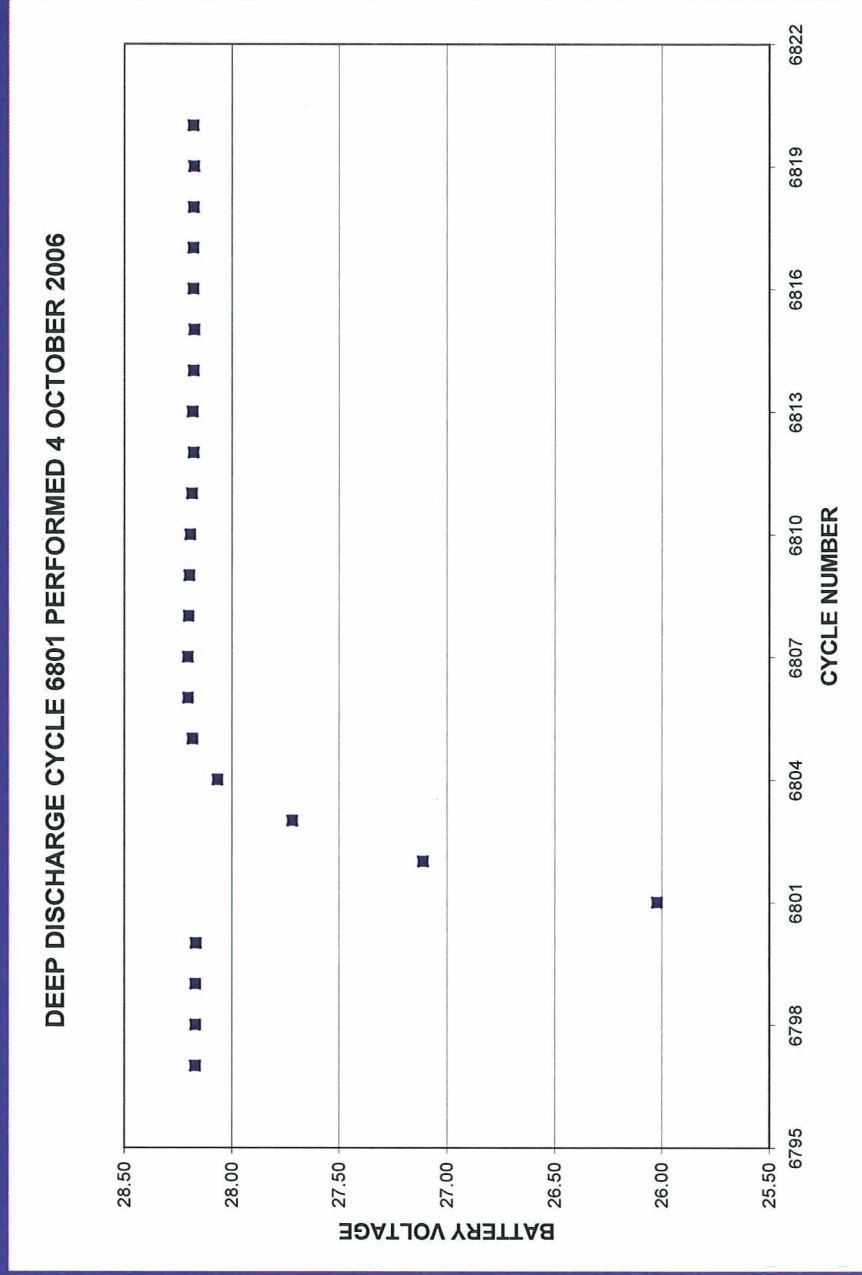
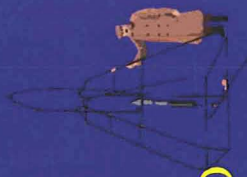






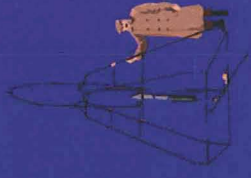
## LLO: Quallion-contd.

A typical Voltage Recovery during normal cycling after the 80% DOD





## LLO: Saft



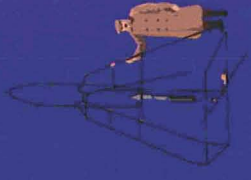
- **Battery Description**
  - 40 Ah Battery
  - 8s
  - Actual capacity at the test start: 49 Ah for a 20 A discharge to 24 V
- **Test Parameters**
  - 42% DOD
  - 113-minute orbit
  - Charge at 23 A to 31.2 V clamp with a taper to end of the charge period of 65 minutes
  - Discharge current 21 A for 48 minutes
  - 80% DOD
  - One 225-minute orbit
  - Charge at 23 A to 32.8 V clamp with a taper to end of the charge period of 65 minutes
  - Discharge current 12 A for 160 minutes





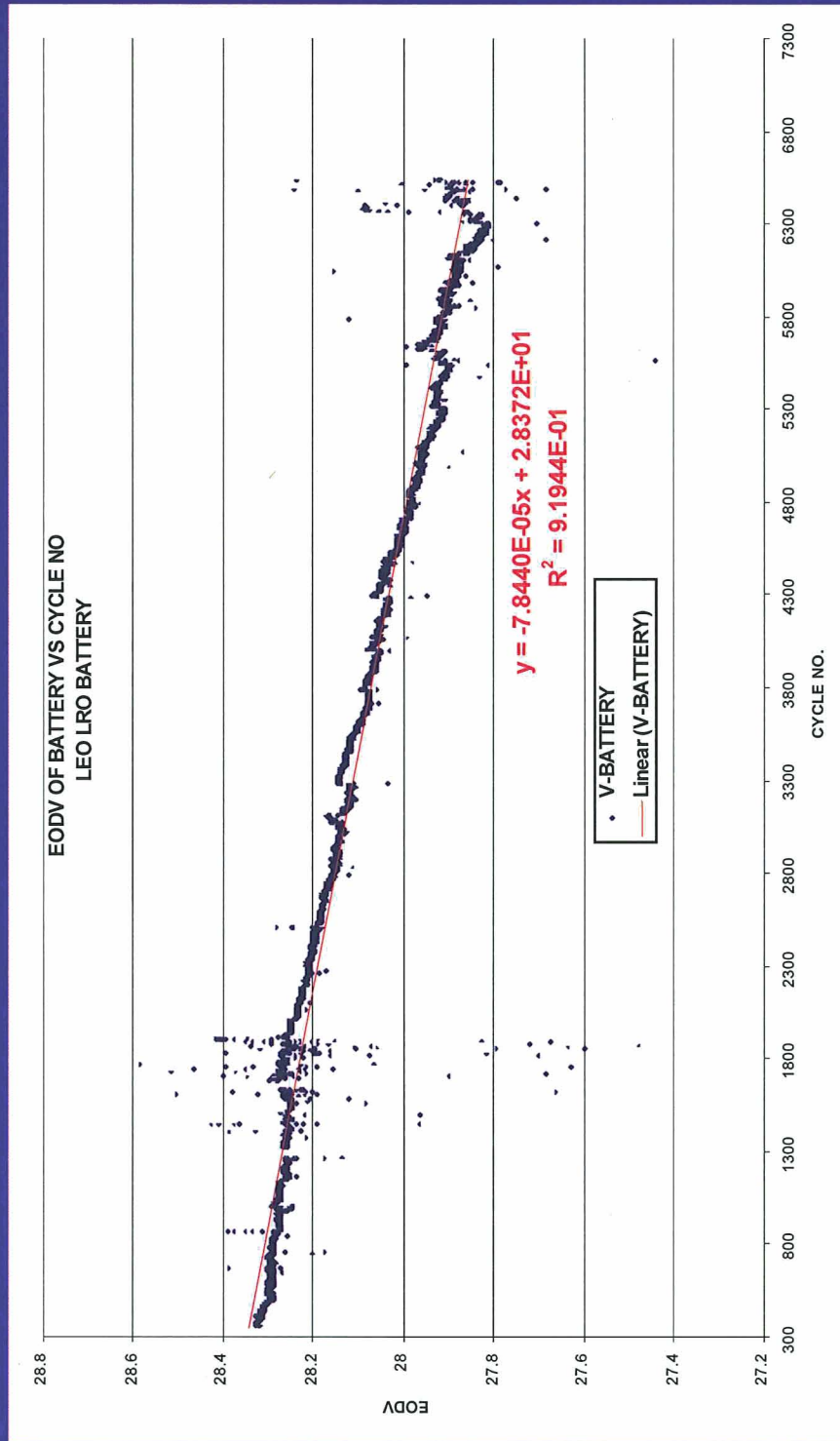
## LLO: Saft-contd.

- Current Status
  - Completed 6790 cycles, of which 1 was 80% DOD
  - EOD 27.86 V for 42% DOD
  - EOD 27.76 V for the last 80% DOD
  - Max. cell voltage divergence 63 mV (during charge), no cell balancing circuitry
  - EOD voltage trend is shown in the following page





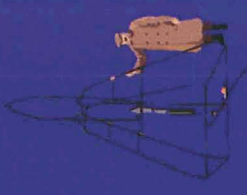
# LLO: Saft-contd.







## LLO: YTP

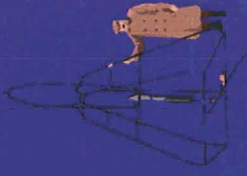


- **Battery Description**
  - 50 Ah Battery
  - 4s
  - Actual capacity at the test start: 58 Ah for a 25 A discharge to 24 V
- **Test Parameters**
  - 40% DOD
  - 113-minute orbit
  - Charge at 22 A to 15.8 V (at battery 31.6 V) clamp with a taper to end of the charge period of 65 minutes
  - Discharge current 22 A for 48 minutes
  - 80% DOD
  - Once in every six months 225-minute orbit
  - Charge at 22 A to 16.4 V (at battery 32.8 V) clamp with a taper to end of the charge period of 65 minutes
  - Discharge current 15 A for 160 minutes



## LLO: YTP-contd.

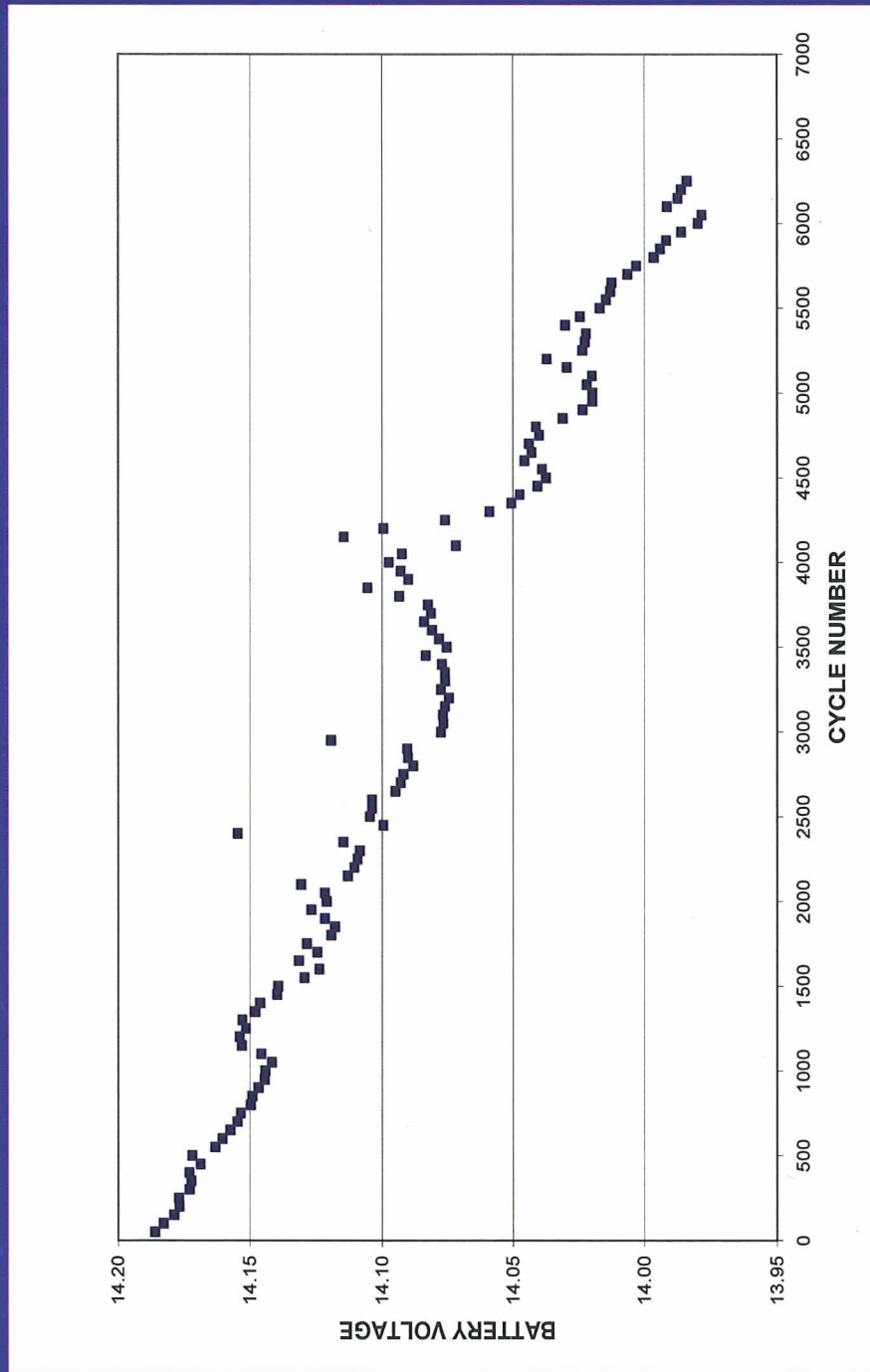
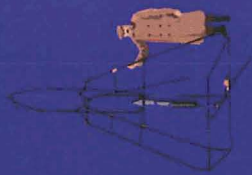
- Current Status
  - Completed 6790 cycles, of which 2 were 80% DOD
  - EOD 13.98 (at battery 27.96 V) for the 40% DOD
  - EOD 13.29 (at battery 26.58 V) for the last 80% DOD
  - Max. cell voltage divergence 291 mV, no cell balancing circuitry
  - EOD voltage trend is shown in the following page





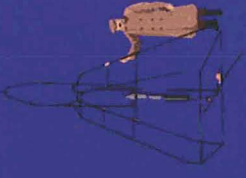


## LLO: YTP-contd.





## Cell Voltage Divergence: ABSL

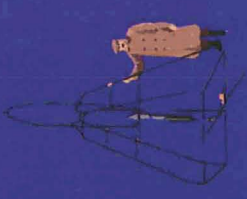


- **Battery Description**
  - 6 Ah Battery
  - 8s4p Sony 1.5Ah cells
  - Actual capacity at the test start: 5Ah for a 3 A discharge to 24 V
  - 1 KHz impedance at the beginning 122 mohms
- **Test Parameters**
  - LEO, 93-minute orbit, charge at 3 A to 33.6 V with a taper to end of the charge period of 57 minutes, discharge current 3 A for 36 minutes, DOD 30%
  - GEO, 24-hour orbit, eclipse regime - charge at 0.3 A to 33.6 V clamp with a taper to the end of the charge period, 42 days eclipse, max. DOD 72%, discharge current 3.6 A, and solstice regime - 140 days, voltage clamp at 32.3 V (72% SOC), fully charged prior to commencement of each eclipse season
  - 900 LEO cycles followed by one real time GEO is one set
  - Capacity and impedance checked prior to starting each set

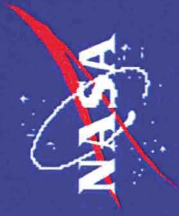




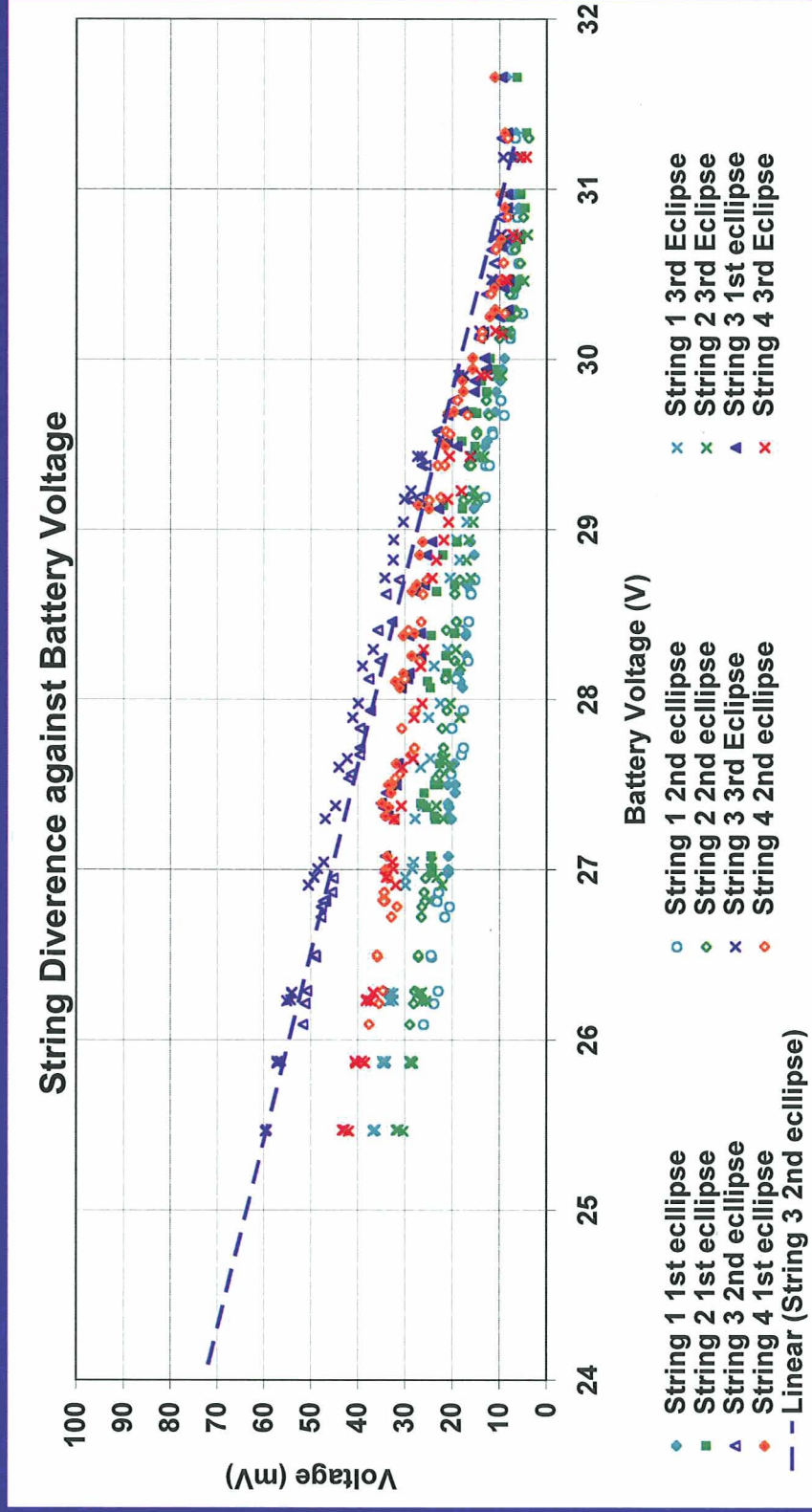
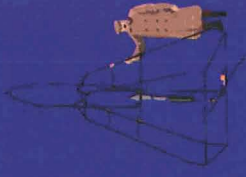
## Cell Voltage Divergence : ABSL -contd.



- Current Status
  - Completed three sets (2700 LEO cycles and 3 real time GEO eclipse solstice), and the capacity and impedance now are 3.8 Ah and 198 mohms
  - Max. cell voltage divergence for LEO 30% DOD is about 8 mV and for GEO 72% DOD is about 60 mV, appears to depend on the actual SOC
  - Estimated max. cell voltage divergence at 24 V now is 75 mV
  - Capacity fade and impedance increase correlate with the prediction
  - Cell voltage divergence with battery voltage trend is shown in the following page



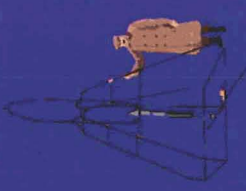
# Cell Voltage Divergence: ABSL -contd.







# Conclusions



- Goddard Space Flight Center has “Pioneered” the rechargeable secondary battery design, test, infusion, and on-orbit battery management among NASA installations for over the last four decades
- Li-Ion Batteries from **Atomic Energy Authority Technology Battery Systems Ltd., (ABSL)**, Japanese Storage Yuasa Technology Ltd. (JSYTL), Quallion, SAFT, **T/J Technologies Inc./A123 Systems**, Yardney Technical Products (YTP)/ Lithion have been designed and tested for aerospace application
- Emerging technology for future NASA missions
- Completed up to three years of real time GEO, LEO and LLO cycles
- Max. cell voltage divergence in ABSL battery using Sony cells appears to depend on the actual SOC
- ST - 5, a four-month mission that was launched in 3/06, was our first technology demonstration in space and the first application of ABSL batteries in America
- Calipso, a three-year LEO mission that was launched in 4/06, was our first battery infusion into our mission





# Conclusions- cont'd.

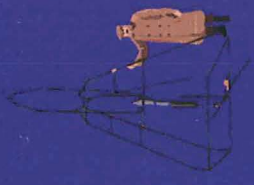


- The battery technology is baselined for Themis (ABSL), SDO (ABSL), LRO (ABSL), IBEX (Yardney) GPM (?) and MMS (?) spacecraft; SDO and LRO batteries are the largest of the ABSL batteries that have ever flown
- MARS (Spirit and Discovery) (8/03), ST-5 (3/06) and Calipso (4/06) spacecraft with Li-Ion batteries are now launched, and Themis is scheduled for launch in January 07; these batteries' ground handling and in-orbit performance will provide valuable experience. The lessons learned will be implemented in the future cell/battery designs, battery ground handling, and the onboard battery management





# Acknowledgment



- Mr. D. Curzon, ABSL, for conducting ABSL batteries testing
- Mr. J. David, NSWCC, for conducting JSB, Quallion, T/J Technologies and YTP batteries testing
- Dr. R. Staniewicz, Saft, for conducting Saft batteries testing
- Mr. D. Sullivan, GSFC, for conducting JSB and YTP batteries testing